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Technical Report

POTENTIAL OF AEROSTATS FOR THE RECOVERY OF DISABLED MAIN BATTLE TANKS AND OTHER HEAVY MILITARY VEHICLES AND EQUIPMENT

by

Thomas Pink

NSWCCD-CISD-2007/012



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Executive Summary

This report describes the investigation of the potential use of aerostats for the recovery of damaged heavy military vehicles such as Main Battle Tanks and other heavy military or relief equipment deployed from a Sea Base. A capability gap was identified for vehicles within the Marine Corp and Army inventory. High value vehicles that will need to be recovered but couldn't be lifted by the heavy lift helicopter CH-53 were identified. Past and current aerostats were researched and the most suitable type, which satisfied most of the key requirements, was identified. The optimum configuration consists of an un-powered 'air-crane' balloon supporting the payload over the balloon's envelope skin through appropriate rigging. The balloon would be towed to its destination by a helicopter, land vehicle or surface vessel.

Preliminary design calculations were performed in the design of the balloon itself and the system required to support it. This enabled an assessment of its feasibility. The concept was developed into a system consisting of two variants of balloon, one with a 40 MT maximum payload capable of lifting loads up to M2A3 Bradley Fighting Vehicles, and the other a 70 MT capacity balloon capable of lifting the M1A1 Abrams Main Battle Tank.

A decision was made to use hydrogen as the primary lifting gas due to its lower cost and the capability of being generated on-site within the Sea Base. Commercial electrolysis units represented a suitable and efficient source of hydrogen, but also place a high power burden on the ship. For rapid reaction, the deflated, packaged balloon would be deployed ashore by helicopter. Additionally, hydrogen would also need to be deployed ashore. A concept system of composite pressure vessels was identified as the most suitable method of rapid deployment. Four to six ISO tank pressure vessels would be deployed ashore to inflate the balloon. The balloon would be secured to the vehicle then both would be towed back to the Sea Base at a speed of between 35 and 55 knots. The feasibility assessment of this system indicated the ISO tank pressure vessel was the critical component. At this time no pressure vessel exists that fulfills the requirement of a low weight, high pressure and quick gas release. Composite pressure vessels represent a possible solution to this problem but further research and development would be required. Therefore the feasibility of both balloon variants at this time with the proposed system is unfeasible, but might be possible in the near future. The 40 MT max payload balloon is the more viable of the two designs due to its lower volume and low cost envelope skin (\$42,000) for cost effectiveness. The 70 MT max payload balloon is less viable due to the long production time for generating the required amount of hydrogen (24 days) and due to the lower cost effectiveness of its expensive envelope skin (\$195,000).

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Introduction

Mission Statement

There is always a need in military deployments to recover disabled vehicles from theatres of operation as they represent a valuable asset. However, most vehicles are too heavy to be lifted by helicopter. Other methods of heavy lift could be utilized to fulfill this role, such as aerostats.

Therefore, the mission of this project is to develop the concept design and modus operandi of an Aerostat vessel capable of recovering disabled heavy vehicles such as main battle tanks. This was envisioned to take place within the Sea Base environment requiring the complete aerostat to be easily stowed at sea and easily deployed ashore. From the outset there was an emphasis to minimize cost and complexity, ideally designing a solution cheap enough to be widely available and expendable if required.

The current air lift capability of any US Marine Corps or US Army deployed force is carried out by their fleet of helicopters, whose maximum lifting loads normally do not extend beyond 16 MT. Aerostat technology has the potential to allow larger amounts of lift to be generated without the complexity of helicopters or air cushioned vehicles. This potential could prove very useful in the recovery of disabled vehicles or static bulk loads beyond the current lift capability. In addition, it also could be used to transport bulk loads in other areas such as relief operations. If vulnerability, control and operation problems can be overcome or mitigated sufficiently the Aerostat concept might offer a desirable solution that allows cheap, large capacity lift operations, albeit at a relatively slow pace.

The recovery of disabled vehicles is advantageous compared to abandoning or destroying them. If repaired, the vehicle can enter back into service recovering the military capability as well as the cost of the vehicle. Also, recovering the vehicle will exclude the possibility of any sensitive technology within the vehicle falling into enemy hands.

Intentions & Constraints

- Current state of the art in Aerostat design shall be assumed
- No personnel shall be embarked on or under the Aerostat and its load during operation
- The concept shall operate as close to ground as possible in the given terrain
- Minimize Sea Base and ashore footprint and manning. Prior to operation the system shall be stowed with the Aerostat deflated
- Minimize cost and complexity

Capability Gap

Before starting a design process, the capability gap for airlifting Marine and Army vehicles has to be established. Examining the current airlifting capacity and comparing it to the individual and overall weights of Marine and Army Vehicles can accomplish this.

Once this capability gap has been established, it will not only confirm a need for a heavy lift aerostat but it will also allow engineers to examine what likely maximum and minimum lifting capacity would be required.

To obtain an accurate representation of future deployed forces, two main groups of vehicles were examined. These main groups were a Marine Expeditionary Brigade (MEB) and an Army Representative Armored Unit (ARAU).

Current Capability

The current lift capability for both the Marine Corp and the Army is the CH-53 Sea Stallion. The Marine's heavy lift helicopter has a range of up to 600 nm with a maximum speed of 150 knots. The CH-53E's maximum lifting capacity or payload is 16 MT (sea level).



Figure 1: US Marine Corp Heavy Lift Helicopter CH-53E Sea Stallion

Marine Expeditionary Brigade

Table 1 shows the assumed payload for the MEB (Source: Sea Base to Treeline Connector Report, NSWCCD-20-TR-2005/05 Aug 2005).

Item	Name	Quantity	Weight (MT)	Total Payload (MT)
M1A1	Abrams Main Battle Tank	14	57.22	801.07
AAAV	Advanced Amphibious Assault Vehicle	48	28.53	1369.44
M88A1	Armored Recovery Vehicle	1	48.93	48.93
M1097	Heavy HMMWV	99	3.86	382.34
M198	Towed Howitzer	18	8	144.02
LVS Mk48	Logistics Vehicle System	2	25.4	50.8
M101A2	Cargo Trailers	20	0.63	12.64
M390	-	21	2.32	48.69
LAV	Light Armored Vehicle	25	15.73	393.19
Mk1 GI Joe	GI Joe	2226	0.2	445.2
FRKLFT	Fork Lift	7	15.02	105.16
AVLB	Armored Vehicle Launcher Bridge	1	54.7	54.7
MEWSS	Mobile Electronic Warfare Support System	3	15.73	47.18
MTVR	Medium Tactical Vehicle Replacement	133	11.79	1568.52
MRC	-	33	4.67	154.18
M9293/Q46	-	4	10.87	43.5
ABV	Assault Breacher Vehicle	2	49.9	99.79

Table 1 MEB Assumed Payload

Figure 2 shows the vehicles the CH-53E Sea Stallion cannot lift.

MEB Equipment Weight with CH-53 Lifting Capacity

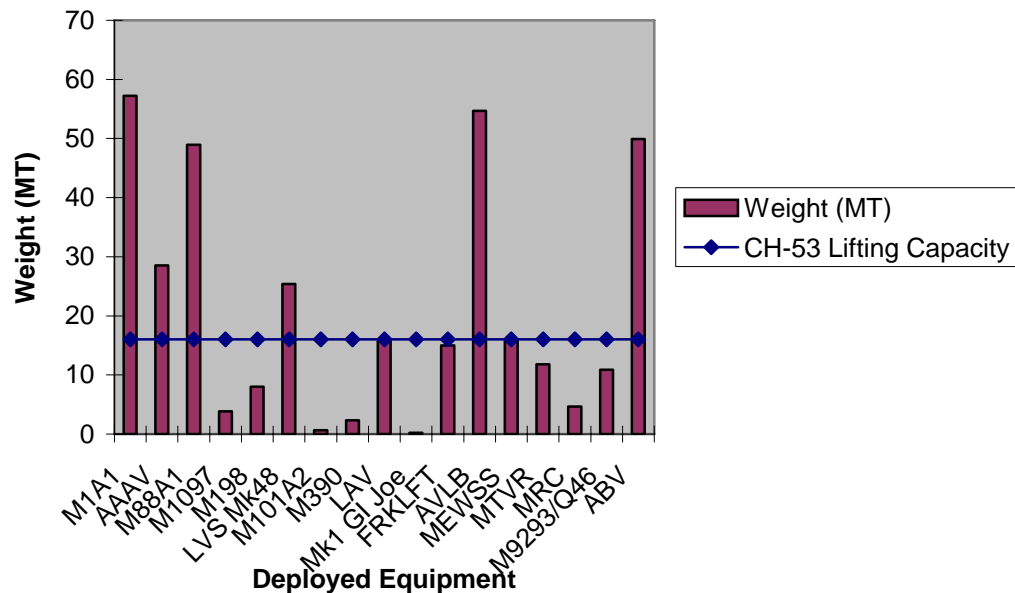


Figure 2: MEB Equipment Weight Comparison with CH-53 Lifting Capacity

Figure 2 shows there are several vehicles in the MEB with weight that exceeds the CH-53E's lifting capacity. There are also vehicles such as the LAV and MEWSS, which are very close to the 16 MT lifting capacity. A 10% weight growth is common for a vehicle going into operations as it is usually fitted with extra equipment and supplemental armor. Therefore, any vehicle whose weight plus 10% is above the lifting capacity should be considered as a marginally liftable weight. With this in mind, Figure 3 represents the current liftable proportion of overall MEB total payload.

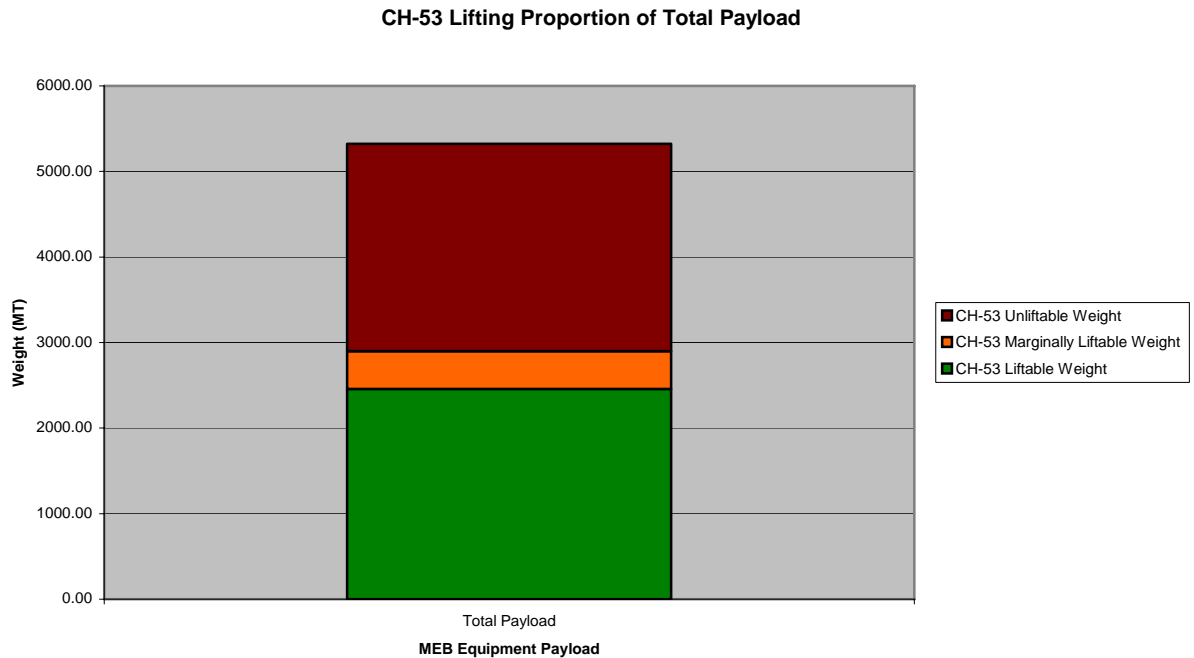


Figure 3: CH-53 Lifting Proportion of Total MEB Payload

Over half of the MEB total payload (shown in red and orange) is either un-liftable or marginally liftable by the CH-53E.

Army Representative Armored Unit

An ARAU would be an Army Unit deployed by a JHSS (Joint High-Speed Sealift) Ship into overseas operations. All data on the number and type of vehicles can be found in Appendix 2 and has been sourced from a 'Military Traffic Management Command' presentation on 'JHSS Army Unit Equipment/Stow Planning' by Terry de Lucia. The below charts represent the ARAU data in the same form as previously for the MEB group of vehicles.

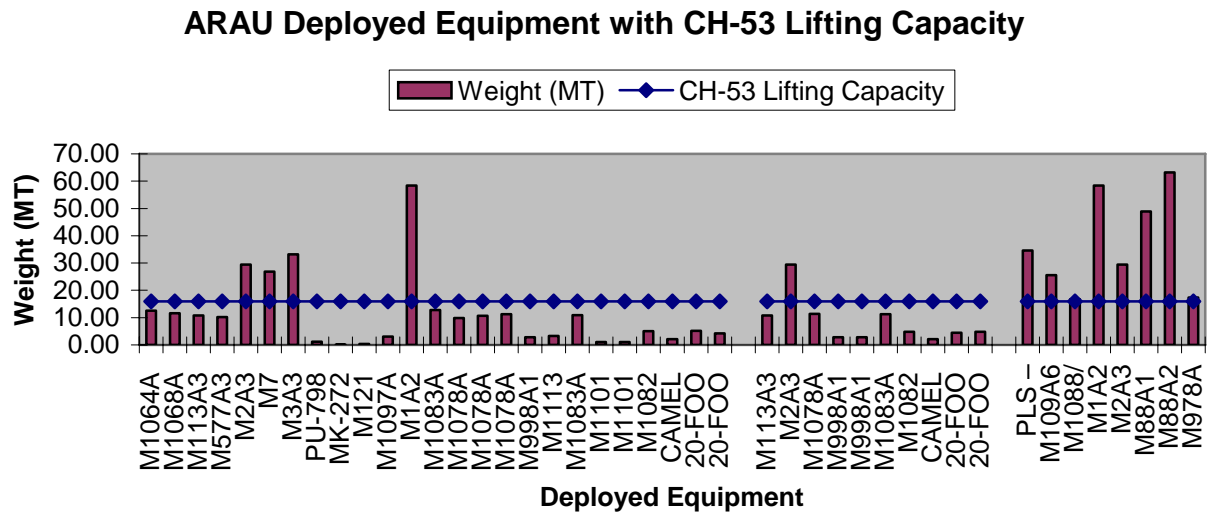


Figure 4: ARAU Equipment Weight Comparison with CH-53 Lifting Capacity

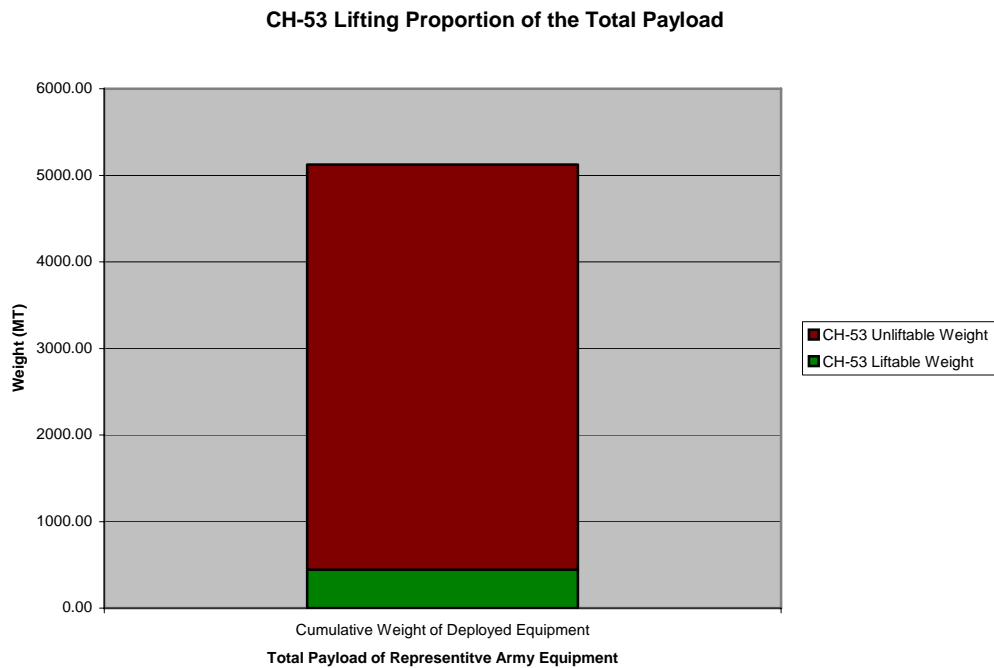


Figure 5: CH-53 Lifting Proportion of Total ARAU Payload

A large proportion of the ARAU total payload (shown in red) is outside of the CH-53E's lifting capacity. This is largely due to the 29 M1A1 Abrams Main Battle Tanks (58.37 MT) and 38 M2A3 Bradley Fighting Vehicles (29.42 MT) within the ARAU.

The above charts illustrate that neither the Army nor the Marines have lift solutions for a large proportion of their fighting vehicles.

Other Military Equipment

Apart from Army and Marine deployable units, there is other military equipment that falls beyond the maximum lifting capacity; it would be advantageous for this equipment to be recovered if it was isolated or damaged. Listed below is some military equipment that requires a heavy lift capability.

Aircraft:

- *F-35 Lightning II* – Empty Weight = 12,000 kg / Loaded Weight = 20,000 kg.
- *F-22 Raptor* – Empty Weight = 14,379kg / Loaded Weight = 25,107kg.
- *V-22 Osprey* – Empty Weight = 15,032kg / Loaded Weight = 21,500kg.

It would be advantageous to be able to recover these aircraft at their loaded weight (with ordnance and fuel still in place).

Small Boats:

- RIBs
- Interceptor Craft
- Small Patrol Boats

Vessels such as the Mark V special operations boat, can weigh up to 57 MT in operational configurations:



Figure 6: Lifting of a Mark V Special Ops Boat

Relief Operations:

- Non-military loads of water, shelter or medical equipment over 16 MT.

The military equipment identified in the preceding sections helps to determine the airlift capability gap that currently exists within the deployed U.S. Armed forces and highlights a requirement for this heavy lift capability.

Vehicles Most Likely To Be Recovered

An airlift capability gap exists between the weight of the first vehicle above the CH-53E maximum lifting capacity and the weight of the heaviest vehicles deployed into operations. Considering the above data, the following vehicles seem to dictate this capability gap:

LAV – Light Armored Vehicle



Figure 7: LAV - Light Armored Vehicle

The LAV is quoted as having a weight of 15.73 MT, which is within the capability of the CH-53E. However, with expected 10% weight growth through the addition of extra armor and additional upgrades, this standard vehicle weight can be expected to reach up to 17.3 MT.

AAAV – Advanced Amphibious Assault Vehicle



Figure 8: AAAV - Advanced Amphibious Assault Vehicle

The AAAV will be the mainstay of the light armored requirement of the future MEB. With a quantity of 48 within each MEB the amphibious vehicle represents a large proportion of the total MEB weight. Each vehicle weighs in over 28 MT, which is well above the CH-53 maximum lifting capacity.

M2A3 – Bradley Fighting Vehicle



Figure 9: M2A3 - Bradley Fighting Vehicle

The M2A3 Bradley Fighting Vehicle is the principal light armored vehicle of the U.S. Army. The M2A3 weighs in at approximately 29.42 MT, and is the largest quantity of any one vehicle deployed into combat, with 52 being deployed within an ARAU.

M1A2 – Abrams Main Battle Tank



Figure 10: M1A2 Abraham Main Battle Tank

The M1 Abrams main battle tank is the principal combat tank of the United States Army and the United States Marine Corps and the heaviest vehicle, of any significant number, deployed into combat. The M1A2 weighs in at approximately 58.37 MT. With the addition of 10% weight growth through its service life, the total weight equals 64.2 MT.

Therefore the airlift capability gap can now be quantified as the following:

17.3 MT – 64.2 MT

However, the capability gap itself is also split into two distinct ranges:

A payload range not including M1A1 and its variants of 17.3 – 40 MT

This consists of the LAV, AAV and the M2A3 and makes up over 78 vehicles in the MEB and 87 in the ARAU. The range extends from the CH-53's lifting capacity of 16 MT (including the marginal cases) up to between 30 - 40 MT if a safety margin and 10% service is included.

A payload range including the M1A1 and its variants 40 – 64.2 MT

This consists of only the M1A1 and its variants, which make up just 18 vehicles in the MEB and 39 in the ARAU.

Due to the small number of vehicles in the extended range of 40 – 64.2 MT, it is important to make a distinction between the two ranges and consider whether it is viable to aim for as large a maximum payload as 64.2 MT. However, as the M1A1 is such an expensive piece of equipment at over \$4,300,000 (source: www.wrc.navair-rdte.navy.mil/warfighter_enc/landcraft/m1a1tank) it is important to consider it in the 'recovery' aerostat requirements.

Background

An aerostat is a vehicle lifted by buoyancy. It has an envelope containing a gas less dense than the surrounding air. The term 'aerostat' comes from the fact that buoyancy is technically said to provide "aerostatic lift" in that the upward force arises without movement through the surrounding air mass.

Aerostats fall into three main categories:

- *Moored Balloons:* moored gas envelopes, which can carry instruments and sensors for long durations that are impractical for other aircraft.



Figure 11: USGS Tethered Balloon

- *Free Balloons:* free moving, un-powered aerostats. An example is hot air balloons, although un-powered balloons do exist which utilize other gases.



Figure 12: Hot Air Balloon

- *Airships*: free flying aerostats that can be propelled and steered and carry out a variety of missions such as advertising.



Figure 13: Goodyear Blimp

Appendix 1 of this report provides background on the evolution of aerostats to aid the reader in their understanding of the different types and to provide evidence of aerostats as an established technology.

Existing Aerostatic Heavy Lift Concepts

This section will describe the current developments in the use of aerostat technology to lift heavy loads to build an understanding of their existing and possible future capabilities to aid in the design process.

In the past decade there have been various commercial and military programs to develop heavy lift aerostats. Some of the most advanced and technically capable examples are described below.

SkyCat

The SkyCat hybrid air vehicles, supplied by Advanced Technologies Group, based in Cardington, Bedfordshire, UK, combines lighter-than-air airship technology and air-cushioned hovercraft technology. It was originally planned to build three variants the SkyCat 20, 220 and 1000 with payload capacities from 20 MT to 1,000 MT.



Figure 14: SkyCat Hybrid Air Vehicle

The SkyCat is designed with an advanced lifting body, which is in the form of an ellipsoidal-shaped cross section hull and catamaran-like hover-cushions. The development of the SkyCat is based on the proven designs by Airship Technologies, which designs and operates numerous passenger airships.

The envelope structure consists of a laminated fabric envelope. This envelope is a large bag containing helium gas, which provides the airship with much of its lift. Helium is an inert gas, which is not flammable. The payload module is built on the centre line of the airship. An internal structure supports the payload. The envelope shape is supported by an internal configuration of diaphragms, which can be used to compartmentalize the structure.

Overall dimensions:	SkyCat-20	SkyCat-220
Length:	81.0m	185.0m
Height:	24.1m	47.0m
Width:	41.0m	77.3m
Payload module:		
Length:	25.5m	64.0m
Height:	2.6m	4.8m
Width:	3.5m	7.8m
Payload:		
Standard STOL mode:	20.0 tons	220.0 tons
Hover/VTOL mode:	14.5 tons	160.0 tons
Range:		
Max payload, at cruise:	2,400 n.miles	3,225 n. miles
Speed:		
Cruise:	75 kts	80 kts
Sprint:	85 kts	95 kts

Table 2: SkyCat Basic Data

Unfortunately in July 2005, Advanced Technologies Group Ltd experienced financial problems that prevented production of any of variants. However a small concept demonstrator 'SkyKitten' was built and proved many of the hybrid air vehicle concepts.

Walrus

The Defense Advanced Research Projects Agency (DARPA) Walrus program's goal was to develop and evaluate a very large airlift vehicle to transport vast amounts of military equipment over great distances. The Walrus airship was designed to meet this requirement and is a heavier-than-air vehicle that will generate lift through a combination of aerodynamics, thrust vectoring and gas buoyancy.



Figure 15: DARPA's Walrus

It was intended to carry a payload of more than 500 tons 12,000 nautical miles in less than seven days at a competitive cost. Unfortunately, funding was cut in the program before any production of prototypes could be carried out.

CargoLifter AG

CargoLifter AG is a German company, which planned to build airships capable of carrying enormous loads for the bulk airfreight market.

CL160

One was the CL 160, a semi-rigid or keeled airship capable of carrying up to 160 metric tons. The envelope is not stretched over a rigid structure but has a keel, which is attached to the bottom of the envelope and distributes the weight of the payload along the length of the envelope. The airship gains all of its lift through 450,000 m³ of helium gas and therefore only requires energy for forward propulsion.

The envelope is constructed of highly leak-proof multi-layer membranes, which minimize the loss of helium. The material is lighter, more stretchable and durable, and less flammable than previously available materials. The keel is made of aluminum with four integrated engine pylons.



Figure 16: CL160

The CL 160 was intended to be able to carry payloads weighing up to 160 metric tons, with a volume of up to 3,200 m³, to a range of up to 10,000 km.

CL75

Another of CargoLifter's major programs was the CL75. This smaller aerostat was unpowered and consisted of a simple balloon envelope containing helium for lift. Rigging then supported a carriage, which was slung underneath the balloon. This carriage contained all the necessary ballasting equipment, which consisted of compressed helium and sand tanks.



Figure 17: CL75 and its Carriage

The balloon was 61m (200 ft) in diameter with a volume of 110,000 m³ and capable of lifting up to 75 metric tons. Once airborne with the load, the balloon would then be towed to its destination using a towing point.

In May 2002, the CL 160 development was halted due to financial problems and the status of the program is uncertain. In June 2002, the company made an application for insolvency. Work on CargoLifter's other major program, the CL 75 lifting balloon, was also halted in August 2002.

Logging Balloons

During the 1990's the company ILC Dover was involved in the design and manufacture of several 'Logging Balloons'. These aerostats were large hot air balloons, which were utilized in the northwestern U.S. and western Canada to retrieve logs from mountainous areas in which logging roads were unavailable or prohibited for environmental reasons.



Figure 18: Logging Balloon

The Logging Balloon shown above has a 33.5m (110ft) diameter, a volume of 17,556 m³ (620,000 ft³) and a lifting capacity of 15 tons.

Aerostat Requirements

The first requirement is the range of loads the aerostat will be expected to lift. Most of this can be deduced from the capability gap that has been identified. However other considerations also have to be taken into account. The capability gap begins at 17.3 MT, ideally the aerostat would be required to lift anything above the CH-53E's maximum capacity. Also it is prudent to implement a 10% safety margin into the maximum lift capacity to allow for any unforeseen circumstances.

Primary Lifting Requirement: Range of 16 – 40 MT

Additional Lifting Requirement: Range of 40 – 70 MT

For the Aerostat to be feasible as a concept for the recovery of disabled vehicles, its cost per deployment needs to be significantly lower than the cost of the vehicle it will recover.

Low Cost per Deployment - Minimize cost and complexity

To minimize the complexity of the system and negate added safety restrictions the following requirement will apply.

No Personnel shall be embarked on or under the Aerostat and its load during operation

For the Aerostat to be easily deployed and cost effective the following requirements should also be considered in the design.

Ideally the whole system will be deployed by one helicopter (CH-53E maximum lift capacity – 16 MT)

Unpacked easily out of one modular container (e.g. ISO Container)

Disposable or easily packed back into its original container

Simple as possible e.g. no complicated control systems

Recovery operation to be completed in one day i.e. one standard day (12 hours of daylight)

Simple Lifting procedures

All of the above requirements are aimed at tailoring a low cost and simple heavy lift aerostat system that can be deployed easily in a short amount of time.

Design Process

The first task in the design process was to determine the type of aerostat best suited to meet the requirements.

Tethered Balloon: A tethered balloon is usually static and rarely carries any significant weight and would therefore be impractical for transporting damaged vehicles.

Airship: As explained in the section of the report entitled Background, there are various different kinds of airships, from rigid manned airships to non-rigid unmanned, that are powered in some way. When lifting heavy loads, usually the rigid or semi rigid airships such as the SkyCat or CL160 concepts perform these tasks. However, these airships cannot be transported in a compact form and involve costly and complex propulsion and flight control systems. Airships are therefore negated from further consideration as an easily deployable heavy-lift solution for the following reasons:

- Hard to deploy, as it cannot be packed into a compact form.
- Complex and costly propulsion system.
- Manned airships incur additional significant safety concerns, un-manned incurs complex control systems.
- Rigid and Semi-rigid airship structures add significant additional weight to the system.

Free Balloon; These are relatively low cost and simple when compared to airships. Their basic components are the envelope and the rigging or carriage to carry any necessary

loads. They represent the most attractive solution to short range 'Ashore to Sea Base' lifting operations for the following reasons:

- Simple and low cost
- Can be packed into a more compact form
- Can be deployed due to its low weight
- Proven lifting concept

Free Balloons are a proven lifting technique as demonstrated in hot air 'Logging Balloons' and by the CargoLifter 75 (see CL75 'Existing Aerostat Heavy Lift Concepts'), which has proven that a helium Free Balloon can lift loads in the magnitude of 75 MT. The disadvantage with Free Balloons is that they are not powered; the CL75's solution was for the balloon to be towed by a land or air vehicle.

Decision Process

As discussed in the above arguments Free Gas Balloon based upon the CL75 concept seems to represent the best solution to pursue further in the design process. A deployable and adapted design around this central concept was pursued.



Figure 19: CL75 In-flight

Further Development

The heavy lift design was adapted around this central concept. However, it did not specify a requirement to use helium as its lifting gas and so alternatives were investigated. There are three main types of gas used in aerostats:

- Hot Air
- Helium
- Hydrogen

Hot Air: Widely used in free balloons around the world, air is simply heated inside a fabric envelope until it has reached a sufficient temperature to generate the required lift. As the air heats up, its density drops and becomes buoyant in the surrounding cold air. Hot air is the simplest and most cost effective form of lifting gas. However it requires around 3 m³ of hot air for every kilogram it can lift (Source: www.chem.hawaii.edu). Therefore to lift 70 MT the balloon would require a volume of 210,000 m³ giving a diameter of 74 m. A balloon of this size would require large amounts of energy through the burning of fuel or some other method to heat it to the necessary temperature and to maintain it throughout the flight. Also, a heavy lift free balloon of this

size is unproven. Due to this energy burden and the mammoth size of the balloon required, Hot Air was not considered for use in this heavy lift aerostat concept.

Helium: Is the most common form of lifting gas used in Airships and Tethered balloons. An inert gas found in North America, it has a lifting power equal to 1 kg of lift per cubic meter. The disadvantage of using helium is primarily its cost at \$2.42 - \$2.63/m³. Therefore it proves very expensive to fill a balloon of a significant size especially when it has to be inflated and deflated regularly between deployments. Since helium can only be obtained through mining, the gas would have to be stored onboard ship inbetween operations and would be a finite supply. However as an inert gas it is predominantly safe.

Hydrogen: Hydrogen was extensively used in airships in the pre-war years before 1940. As indicated in the Background section, vast airships were built containing tens of thousands of cubic meters of hydrogen. Hydrogen is a diatomic gas and has a lifting power marginally better than helium at 1.1 kg of lift per cubic meter. Due to hydrogen's combustible nature, many countries have banned the use of hydrogen as a lift gas for manned vehicles. The Hindenburg disaster is frequently cited as an example of the risks posed by hydrogen. The high cost of helium (compared to hydrogen) has led researchers to reinvestigate the safety issues of using hydrogen as a lift gas. With good engineering and good handling practices, the risks can be significantly reduced. It has been suggested that policy might allow hydrogen for unmanned cargo airships. An advantage of using hydrogen is that it can be generated on site through various reforming or electrolysis methods, therefore negating the need of storing the gas long before it is actually needed.

Therefore for the purposes of this study, due to its low cost and ability to be generated on-site, hydrogen was used as the primary lifting gas. All associated systems will be designed around this fact. However helium with its obvious advantage as an inert gas was paid due consideration throughout this exercise to develop a solution that could potentially use both if required.

Central Concept

The first step in the design process was to calculate the size of the balloon required to lift the maximum load of 70 MT. The balloon was designed to be as simple as possible to avoid expensive complexities. Before design work could begin, balloon envelope material and lifting methods were investigated, as their weight contributed to the total lifting requirement of the balloon.

Balloon Envelope

Most modern free balloon envelopes are constructed from lightweight and strong synthetic fabrics such as Ripstop Nylon, or Dacron (a polyester). The material is cut into panels and sewn together, along with structural load tapes (webbing) that carry the weight of the gondola or basket. The fabric may be coated with a sealer, such as silicone or polyurethane, to make it impermeable to air.

For a free balloon of this heavy lift application, the envelope will have to inhibit helium/hydrogen permeability and provide a high strength to weight ratio. Aerostat envelope materials do exist that carry out this role, such as:

- *Polyether Polyurethane Skin*: Two layers of polyether polyurethane film sandwiching a strength layer of unwoven fabric or lightweight biaxial Kevlar cloth. Weight = 0.15 kg/sq.m (4.5oz/sq.yd). (Source: AIAA Lighter Than Air Conference 1993 p.82)
- *TCOM aerostat fabric*: A durable field-proven fabric constructed of strong Tedlar and Dacron layers bonded by a TCOM proprietary resin.

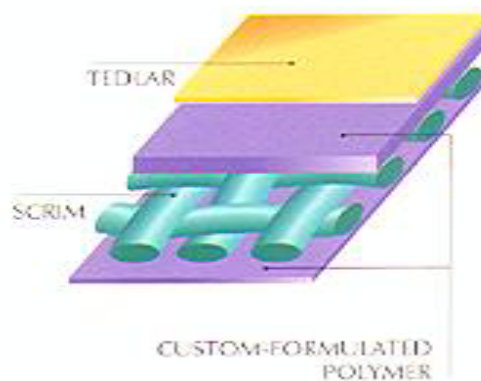


Figure 20: TCOM Multi-Layered Aerostat Fabric

This multi-layered laminate is designed to withstand the sun's UV rays, acid rain and other environmental concerns. It is a tough laminate, which inhibits gas loss while providing a high strength-to-weight ratio.

The CL75 envelope used a laminate material woven with liquid crystal polymer yarns, which were utilized to reduce system weight. It was also constructed with an outer Tedlar® film, which is impervious to the degradation effects of the environment and

gives the balloon a long life of over 10 years. However both of these additions result in a very expensive balloon envelope.

A fabric for the 'recovery' aerostat would have to comprise of the following characteristics:

- High strength; to support the load.
- Low permeability to helium and hydrogen.

Long life is not a requirement. To keep the balloon as simple as possible and to mitigate lengthy re-packing procedures, the balloon would ideally be cheap enough to be disposed of after use. Therefore, a Tedlar® outer layer for environmental protection is unnecessary.

The CL75 was a pressurized balloon using an inner bag ballonet, which is actively filled with air to maintain the desired internal pressure. The main advantage of actively pressurizing the balloon is that the balloon's shape is maintained. The CL75 exhibited good aerodynamic properties when tested. This is due to its ability to maintain a spherical shape and not to be manipulated into an un-spherical shape by wind loads. This would create a 'sail effect' and unbalance the balloon in flight. An additional benefit of an actively pressurized balloon is the ability to adjust the pressure during flight to maintain altitude due to atmospheric changes.

To avoid added complexities in the system and to keep the balloon envelope itself as simple as possible, the 'recovery' aerostat will be designed as an un-pressurized balloon. To minimize the 'sail effect' a 'balloon collar' will be designed to maintain the balloon's spherical shape in flight. As the balloon will only be used over short distances it is deemed un-necessary to adjust its internal pressure in-flight, as it is assumed that atmospheric changes will be negligible. This will be explained further in sections of the report entitled Balloon Collar and Flight Characteristics.

The balloon envelope for the recovery aerostat application would not consist of an internal membrane 'ballonet' or an outer Tedlar® film. It would simply consist of a polymer skin impermeable to hydrogen with a high modulus laminate. This concept was presented to ILC Dover, a balloon envelope manufacturer with a proven track record in manufacturing materials for heavy lift aerostats. They were asked to respond with low cost and low life materials suitable for a range of heavy lift payload. ILC Dover's recommendations were:

- 20 MT payload: A vinyl coated polyester laminate at a weight of 0.667 kg/m² (18.0 oz/yd²) and cost of \$4.80/ m² (\$6.00/linear yard).
- 40 MT payload: A vinyl coated polyester laminate at a weight of 0.816 kg/m² (22.0 oz/ yd²) and cost of \$7.20/ m² (\$9.00/linear yard).
- 70 MT payload: A vinyl or urethane coated high modulus laminate (perhaps Kevlar) at a weight of 0.519 kg/m² (14.0 oz/ yd²) and cost of \$24.00/ m² (\$30.00/linear yard)

(Source: ILC Dover, Assumption; 1 linear yard = 1.5 yd²)

Forty MT is approximately the limit for vinyl coated polyester laminate given a reasonable safety factor for the low cost material. This links well with the primary maximum lifting requirement of 40 MT and consists of the following envelope characteristics:

$$\text{Envelope Weight} = 0.816 \text{ kg/ m}^2$$

$$\text{Envelope Cost} = \$7.20/ \text{ m}^2$$

A balloon capable of carrying the additional payload requirement of up to 70 MT would require a vinyl coated Kevlar laminate. This is due to the high strength requirement to support a load of this magnitude on the balloon's skin alone. This material gives the following balloon envelope characteristics:

$$\text{Envelope Weight} = 0.519 \text{ kg/m}^2$$

$$\text{Envelope Cost} = \$24.00/ \text{ m}^2$$

Considering the expected size of the balloon, the high cost of this envelope skin makes the likelihood of being able to reach the high payload requirement with a low cost balloon unlikely. If this balloon can be developed as a re-useable concept, it might still be of use in recovery scenarios.

Therefore at this stage in the design process the 'recovery' aerostat was split into two variants. The first variant met the primary maximum payload requirement of 40 MT. The second variant met the additional maximum payload requirement of 70 MT.

Rigging

The rigging arrangement is envisioned to be similar to the proven method used by the CL75. Load bearing ropes will be positioned as a wide spaced net over the balloon and will be fixed to its skin in various places, as shown in Figure 20. This configuration will distribute the load over the surface of the balloon.



Figure 21: CL75 Rigging

The CL75 has a heavy carriage system under-slung in which it positions its payload.



Figure 22: CL75 Carriage

This carriage contains a wide-open space for tracked and wheeled vehicles as well as ballasting equipment. This carriage is both expensive and adds significantly to the aerostat's overall weight. It would therefore be advantageous to design the added load of an under-slung carriage.

Most land military vehicles (including M2A3 and LAV) and ISO containers have a requirement to be top lifted by a crane. This means that these vehicles have lifting points on their topside. These can be taken advantage of in the 'recovery' aerostat

scenario. Connecting directly onto the vehicles when they are being lifted would negate the need for an expensive and heavy carriage system.

By doing this, the capability for variable ballasting during flight is lost. This is necessary to traverse distances with no payload and to increase and decrease the balloon's height during flight. The need for this complicated ballast system can be avoided by incorporating some flight restrictions and simple ballast devices. This will be explained further in the section entitled Flight Characteristics.

Lifting of Military Vehicles

Figure 22 shows the lifting configuration for the heaviest military vehicle in the Marine Corps and Army itinerary, the M1A1 Main Battle Tank (Source: Marine Lifting and Lashing Handbook, MTMCTEA REF 97-55-22).

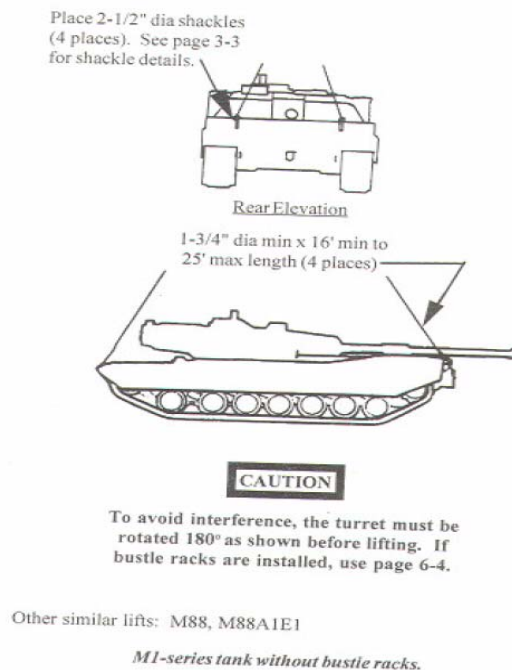


Figure 23: Lifting Configuration of a M1A1 Main Battle Tank

As shown, the M1A1 can be lifted directly from its four topside lifting points. After researching through the Marine Lifting and Lashing Handbook it was found that this lifting procedure was the same for nearly all of the military vehicles in the Marine and Army inventory.

There are several exceptions in this case. When the lifting points cannot be directly accessed from an angle, a spreader bar is required. The picture below shows the lifting of a M1A1 with a rear bustle rack, which restricts direct access to the rear lifting points.



Figure 24: Lifting of M1A1 Main Battle Tank with spreader bars

This is also the case for the M88 Hercules tank and the M110A2 Howitzer. Therefore, it is prudent to keep a couple of sets of spreader bars in reserve if needed and then deploy them when necessary. The number of vehicles in the itinerary that need spreader bars to be lifted is small compared to the overall number of vehicles, therefore a decision has been made to not include the spreader bar as part of the overall ‘recovery’ aerostat system.

Rigging Weights and Sizes

The lifting of military vehicles using the ‘top lifting points’ is an established procedure and further discussion on different methods is not required. For the purpose of the preliminary calculations, only the size and weight of the rigging that is to be used are required. These weights and sizes are sourced from established rigging companies, some of which already supply lifting equipment to the U.S. Armed Forces.

Balloon Rigging

This is the rigging that acts as a wide spaced net and distributes the load over the balloon’s envelope. It is a wide spaced net similar to the CL75 rigging. Six main support ropes will span from the top of the balloon around the middle until they connect onto a main shackle situated directly underneath the balloon.

The rope to be used in the preliminary calculations is Lifting & Safety Services fiber core ropes.

Aerostat - 40 MT Max Payload

A rope with a diameter of 13mm has been chosen to represent what could be used. This rope has a minimum-breaking load of over 10 MT. With six ropes supporting the load, this gives a combined maximum load of 60 MT well above the proposed maximum payload, giving the rigging a safety factor of approximately 1.5. A full description of this rope, along with a range of alternative ropes can be found in Appendix 3.

Diameter = 13mm
Mass = 61.1 kg/100m
Maximum Load = 60 MT

Aerostat - 70 MT Max Payload

A rope with a diameter of 18mm was chosen to form the balloon rigging, this rope has a minimum breaking load of over 19 MT. Therefore with six ropes supporting the load this gives a combined maximum load of 114 MT well above the proposed maximum payload, giving the rigging a safety factor of approximately 1.6. A full description of this rope along with a range of alternative ropes can be found in Appendix 3.

Diameter = 18mm
Mass = 117 kg/100m
Maximum Load = 114 MT

Spacers

Spacers will also be required to complete the netting. Since the balloon will be operated over a range of payloads, these spacers will have to be densely placed at the top of the balloon to support the load over the envelope skin at small inflations. The spacers will be fiber rope but will be required to carry significantly less load and therefore will be smaller and lighter. To obtain a general weight figure, the weight of these spacer ropes will be represented by three balloon circumferences of the heavier load carrying rope.

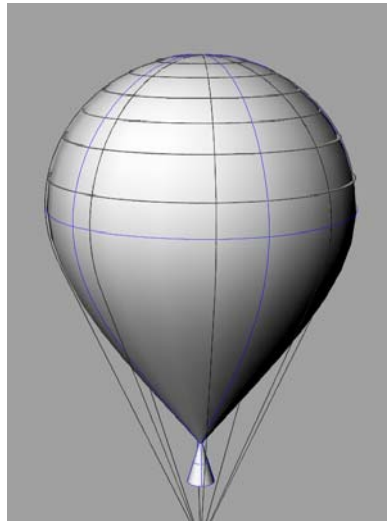


Figure 25: Balloon Rigging

To calculate the total weight of the balloon rigging, the following formula will be used:

$$\text{Length of Rope} = 6 * (0.5 * 1.1 * 2\pi r) + (3 * 2\pi r)$$

Where:

r = Radius of the Balloon

1.1 - Represents the excess required to hang below the balloon while fully inflated

$$\text{Weight of Balloon Rigging} = \text{Length of Rope} * \text{mass per meter}$$

Payload Shackle

The balloon rigging will be attached to the load under-slung below the aerostat via a 'Bolt Type Anchor Shackle'. The following I&I Slingmax shackle will be used for this design.



Figure 26: I&I Slingmax Shackle

Working Limit = 85 MT
Weight = 43.5 kg (96 lbs)

Payload Rigging

The rigging used to lift the actual payload will be representative of what is currently being used in the U.S. Armed forces. These are I&I Slingmax slings. As far as this report is concerned, one set of slings will be used, which are rated to lift a M1A1 tank. The weight of these slings is negligible and has not been considered in the preliminary calculations.

Balloon Sizing

A spreadsheet was developed for both the 40 MT and 70 MT design concepts. This spreadsheet incorporated the balloon envelope weight and the weight of the rigging involved into an overall balloon weight calculation. This total weight could then be used to calculate the volume of gas required to lift the load. To start the calculation, the volume of hydrogen required to just lift the maximum payload alone was calculated.

Hydrogen Lifting Power = 1.1 kg/m³
(Source: Los Alamos National Labs; 0.07lb/ft³ at 0°C 760mm pressure)

The amount gas required to lift 40MT (40,000kg) is as follows:

$$40,000/1.1 = 36,363 \text{ m}^3$$

The amount gas required to lift 70MT (70,000kg) is as follows:

$$70,000/1.1 = 63,636 \text{ m}^3$$

This produced an initial volume for the balloon where sizing could be calculated, which then enabled envelope and rigging weights to be calculated. This produced an 'Aerostat Mass,' which could then be inputted into the beginning of the design calculation as an addition to the overall weight, increasing the volume of gas required to lift the aerostat. At this stage a design was iterated until final aerostat characteristics emerged, as follows:

Balloon - 40 MT Payload

Using Hydrogen: Lifting Power of 1.1kg/m ³ (Source: Los Alamos National Labs; 0.07lb/ft ³ at 0C 760mm pressure)			
Payload (kg)	Aerostat Mass	Total Mass	
40000	5264.99	45264.99	
Balloon Volume m ³			
41149.99			
Envelope Material	Kg/m ²	Mass of the Envelope	
A vinyl coated polyester laminate	0.816	4703.50	
Sphere Balloon Dimensions			
Inner Radius (m)	Outer Radius (m)	Surface Area (m ²)	Circumference
21.42	21.42	5764.09	134.57
Rigging:			
Type of Rope	Length Of Rigging (m)	kg/100m	Mass of Rigging
L&SS Fibre Core (D=13mm)	847.78	61.10	517.99
Payload Shackle	Mass (kg)		
I&I Slingmax 85MT Bolt Type	43.50		
			Aerostat Mass
			5264.99

Table 3: Sizing Spreadsheet for 40 MT Payload Balloon

Balloon - 70 MT Payload

Using Hydrogen: Lifting Power of 1.1kg/m³ (Source: Los Alamos National Labs; 0.07lb/ft³ at 0C 760mm pressure)			
Payload (kg)	Aerostat Mass	Total Mass	
70000	5424.08	75424.08	
Balloon Volume m ³			
68567.35			
Envelope Material	Kg/m ²	Mass of the Envelope	
Vinyl or urethane coated high modulus laminate	0.519	4204.65	
Sphere Balloon Dimensions			
Inner Radius (m)	Outer Radius (m)	Surface Area (m ²)	Circumference
25.39	25.39	8101.44	159.54
Rigging:			
Type of Rope	Length Of Rigging (m)	kg/100m	Mass of Rigging
L&SS Fibre Core (D=18mm)	1005.07	117	1175.93
Payload Shackle	Mass (kg)		
I&I Slingmax 85MT Bolt Type	43.5		
			Aerostat Mass
			5424.08

Table 4: Sizing Spreadsheet for 70 MT Payload Balloon

The above spreadsheets calculate a final maximum balloon radius, through the following calculations (70 MT Balloon has been used as an example):

$$\begin{aligned} \text{Balloon Volume} &= \text{Total Mass} / 1.1 \\ &= 75,424.08 / 1.1 = 68,567.34 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{Balloon Radius} &= (\text{Volume} / (4/3 * \pi))^{(1/3)} \\ &= (68567.34 / (4/3 * \pi))^{(1/3)} = 25.39\text{m} \end{aligned}$$

$$\text{Surface Area} = 4 * \pi * r^2 = 4 * \pi * (25.39)^2 = 8101.44 \text{ m}^2$$

$$\text{Circumference} = 2 * \pi * r = 2 * \pi * 25.39 = 159.5\text{m}$$

$$\begin{aligned} \text{Mass of Envelope} &= \text{Surface Area} * \text{Mass of Envelope Material (kg/m}^2\text{)} \\ &= 8,101.44 * 0.519 = 4,204.65 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Length of Rigging} &= (6*(0.5*1.1*\text{Circumference})) + (3*\text{Circumference}) \\ &= (6*0.5*1.1*159.5) + (3*159.5) = 1,005.07\text{m} \end{aligned}$$

$$\begin{aligned} \text{Mass of Rigging} &= (\text{length of Rigging}/100)*\text{Mass of Rigging per 100m} \\ &= (1005.07/100)*117 = 1,175.93 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Aerostat Mass} &= \text{Mass of Envelope} + \text{Mass of Rigging} + \text{Mass of Shackle} \\ &= 4,204.65 + 1175.93 + 43.5 = 5,424.08 \text{ kg} \end{aligned}$$

$$\text{Total Mass} = \text{Payload} + \text{Aerostat Mass} = 70,000 + 5,424.08 = 75,424.08$$

These calculations give a good representation of the balloon's size and mass allowing more accurate considerations of the accessory equipment to be made.

Flight Characteristics

The aerostat balloon will act as an air-crane. Since it is not powered, it will need to be assisted in flight to accomplish any significant forward airspeed. This will be accomplished by towing the loaded balloon. In theory, the balloon can be towed using the following methods.

- Helicopter
- Boat
- Land vehicle

The boat and land vehicles are limited to one area of operation, sea and land based operations respectively. As it is envisioned to use the 'recovery' aerostat in a Sea Base environment where a vehicle will be recovered ashore and transported back to the Sea Base, a towing vehicle capable of traveling over land and sea is required. The helicopter option is thus a logical option. It gives unparalleled capability of being able to loiter over an area of operation and transverse over sea and land.

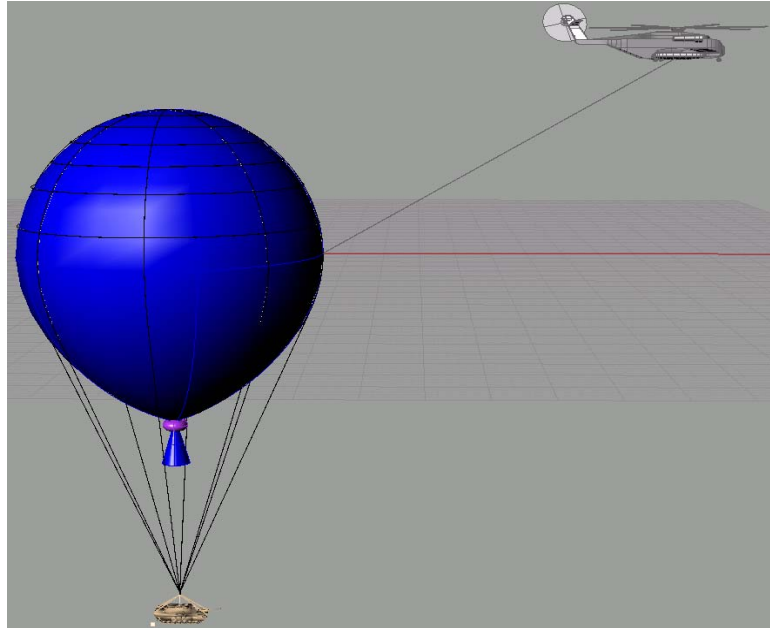


Figure 27: Helicopter Towing the Balloon

There is a distinct lack of published data on the aerodynamic properties of large spheres with high Reynolds (Re) numbers, probably due to the lack of large wind tunnels capable of performing these kinds of tests. After researching established towing methods, consulting with ILC Dover, and by performing aerodynamic drag calculations, (as shown in the Aerodynamic Properties section) it became clear that unacceptable drag forces acted on the variants of the towed balloon at greater than the following speeds.

	40 MT Max Payload Balloon	70 MT Max Payload Balloon
Max Steady State Speed	45 knots	35 knots
Max Surge Speed	55 knots	45 knots

Table 5: Balloon Operating Speeds

The drag forces are also exaggerated for un-pressurized balloons due to wind forces, creating what is called a ‘sail effect’ (source: ILC Dover) by deforming the balloon’s shape. Any un-pressurized balloon is usually limited to all wind conditions below that of 20 knots (sea state 5). This severely limits the balloon’s operational capability. To avoid large sail effects and to maintain the balloon’s shape in flight, a balloon collar will be utilized. The design and operation of this equipment is contained in the section on the report entitled Balloon Collar.

Balloon Ballasting

With all long-range aerostats, ballasting is an established method of maintaining altitude due to atmospheric changes and gas leakage. However, with this design, an attempt is not to include ballasting equipment in an effort to avoid the cost, weight and complexity of the associated equipment.

This is possible because the ‘recovery’ aerostat only has to travel short distances for a limited duration. Operational flight would be achieved by over-filling the balloon, then letting it rise to an altitude where it is at equilibrium with the surrounding atmosphere. Lightweight solenoid valves would be integrated to the top of the balloon’s envelope skin and would open to release hydrogen when a decrease in altitude is required.

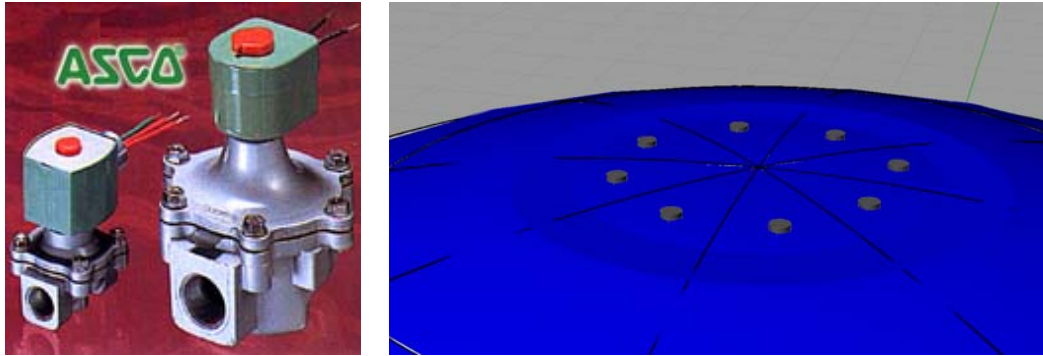


Figure 28: Aerostat Solenoid Valves

A simple method that could be used to increase altitude slightly would be to attach sandbags/ballast weights to the vehicle via a remote controlled clamp. This clamp would then be released mid-flight to drop a sandbag or multiple sandbags when an increase in altitude is required.

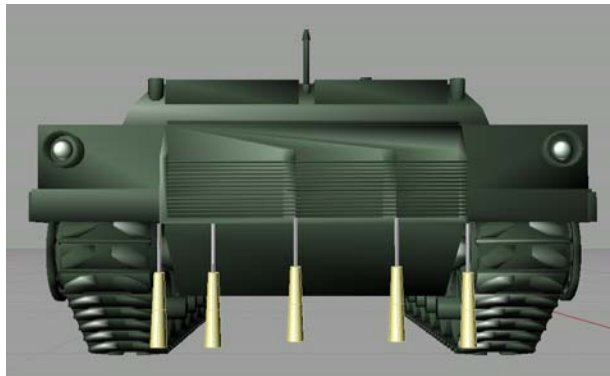


Figure 29: Tank Ballast Weights

Balloon Collar

The ‘Balloon Collar’ is a relatively simple and cost effective means of maintaining the balloon’s spherical shape during flight. Without such a device and at lower payloads, (<40 MT or <70 MT for each design) the balloon would not create a spherical shape; instead excess envelope material would hang below to create a cone like shape.

The collar is unproven technology and would require a great deal of testing and possible redesign before it could operate effectively. In its simplest form, the ‘Balloon collar’ would consist of a vinyl coated polyester laminate donut, which would be attached to remotely operated gas canisters.

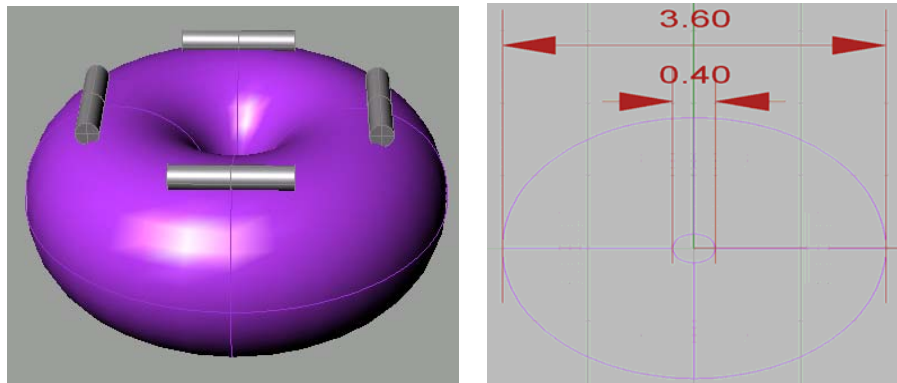


Figure 30: Balloon Collar

This 'Balloon Collar' would have all but the amount of envelope required to fill up to the minimum lifting capacity (16 MT or 40 MT), fed through its center. Rigging would cease to be attached to the balloon envelope at this point. The balloon would be inflated through a pipe, which would pass through the center of the collar beneath the envelope skin. This flexible pipe would then hang off the internal part of the top 'cone' of the balloon, inflating it from the top.

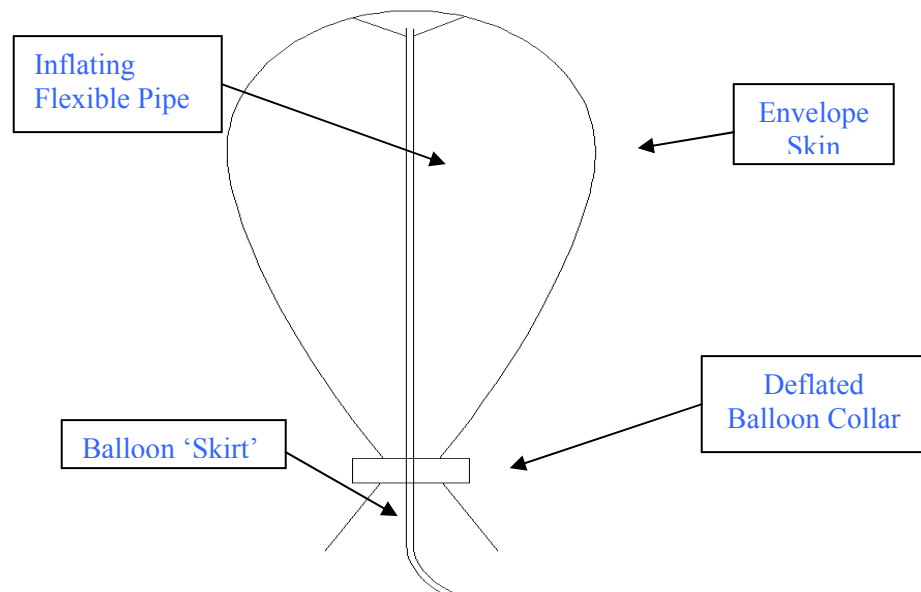


Figure 31: Balloon Cross-Section

The balloon collar would then be semi-inflated to create enough frictional resistance against the balloon skin to stay in place, but not enough to close the flexible pipe. As the balloon is inflated, the envelope beneath it would be held as a skirt to maintain the collar position.

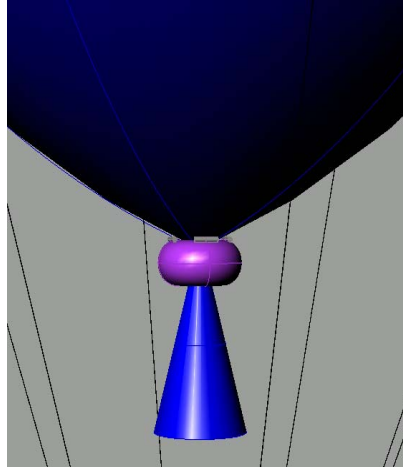


Figure 32: Balloon Collar Skirt

As inflation continues, the collar would slide down the neck of the balloon until it reached a position where the aerostat had attained its required lifting capacity. At this point, the 'Balloon Collar' would be inflated fully at high pressure to form a tight seal around the neck of the balloon and maintain a near spherical shape in flight.

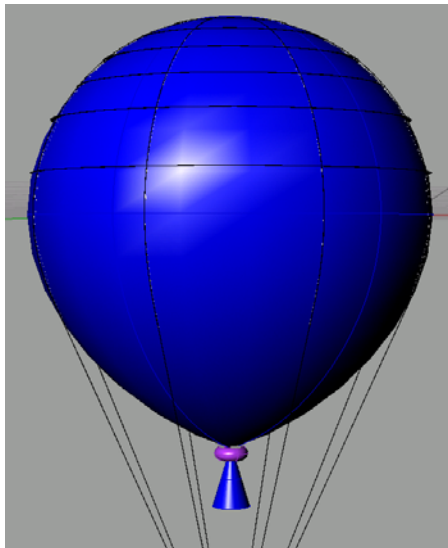


Figure 33: Balloon Collar Securing Inflated Balloon

This collar is an untested conceptual design. However this design or similar concept would be an effective means of maintaining the balloon's shape during flight, which would increase its operational maximum airspeed. It is not an essential part of the design as the balloon could still operate without it at lower wind speeds (<20 knots) with the excess balloon envelope material hanging below it at lower than maximum payloads.

Hydrogen Storage

For the 'recovery' aerostat to be capable of lifting a payload of between 16 and 70 MT. up to 68,000 m³ of hydrogen must be deployed and produced within a short period

of time. Several options were considered. Key characteristics were low total system weight and rapid production time.

Metal Hydrides

After consulting with Dr. Carole Read at the Department of Energy, metal hydrides were introduced as an effective way of storing significant amounts of hydrogen. Complex metal hydrides such as alanate (AlH_4) can, when catalyzed with titanium dopants, produce up to 3.7 wt.% of hydrogen. This is a relatively high weight percentage when compared to other metal hydrides or hydrocarbons. However over 3 MT of hydrogen is required to fill the 70 MT payload balloon to its maximum lifting capacity. This would mean that over 81 MT of alanate would be needed to be deployed to fill the 'recovery' aerostat. This amount is unfeasible and rules out metal hydrides as a viable option for deployable hydrogen.

Pressure Vessels

After further consideration, pressure vessels seemed like the only effective way of storing large amounts of hydrogen with the capability of quick release if required. Yet it soon became clear that storing over large amounts of hydrogen within a confined space at low weight is a difficult task.

State of the art pressure vessels such as the one below manufactured by Hanson Tanks have high capacity but at low pressures of about 10 Bar.



Figure 34: Large Capacity Pressure Vessel (Source: Hanson Tanks)

To store all the necessary gas required at this pressure, a tank volume of over 6,800 m³ would be required. It would be unfeasible to store a tank of this size on board a ship. It would also be very difficult to deploy ashore and impossible to deploy by air.

Ideally, for ease of transport and storage, there would be multiple pressure vessels of a uniform size, small enough to fit within an ISO container or ISO sized framing (ISO tank). To limit size and weight it was decided to limit the size to the smallest ISO containerization available 20ft.



Figure 35: 20ft ISO Tank and Container

The external dimensions for a standard 20ft ISO container are as follows:

20 ft ISO Container	
Length	6.20 m (20' 4")
Width	2.44 m (8')
Height	2.59 m (8' 6")

Table 6: Dimensions - 20ft ISO Container

To identify the characteristics of the ISO sized tanks that would be required, an understanding of the gas laws involved is required.

Ideal Gas Law

$$PV = nRT$$

P = Pressure

V = Volume

n = Number of Moles

R = Gas Constant = 8.2058 (J/K/mol)

T = Temperature

To reduce volume, either pressure has to be increased or temperature decreased or possibly a combination of both these methods could be used. To identify the characteristics and therefore type of ISO tank suitable for this storage task, a graph was compiled that mapped the required moles of gas (68,000 m³ at sea level) against differing pressures and temperatures. This was calculated with a set volume, which depended on the number of ISO tanks it was plotted against. A standard ISO tank pressure vessel's wall thickness was assumed to be 0.1 m producing a volume of 24 m³. A sample of the input spreadsheet for the following graph can be found in Appendix 4.

**Pressure vs Temperature of 68,000 m³ of Hydrogen (ISA Sea Level)
within ISO tanks**

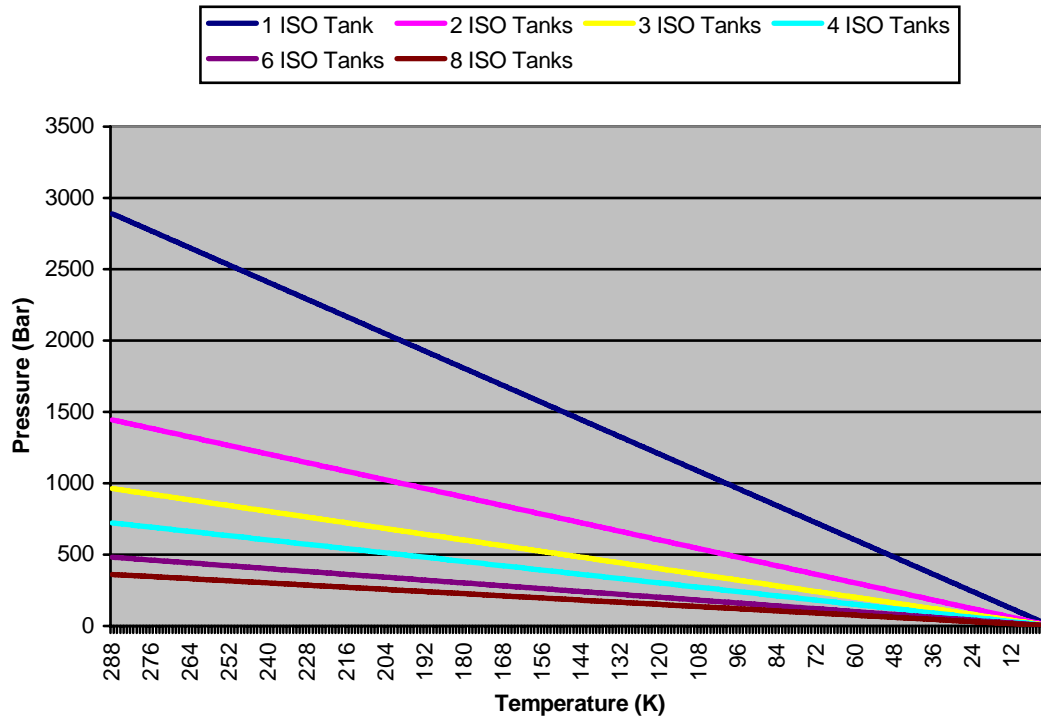


Figure 36: Pressure vs Temperature of 68,000 m³ of Hydrogen (ISA Sea Level)

To store all of the necessary hydrogen gas within one ISO tank, a pressure of nearly 3,000 bar would be required or a refrigeration down to extremely low temperatures. To even reduce the pressure to below 2,000 bar, the tank would need to be refrigerated to below 200°K. It would be unfeasible to store hydrogen onboard a ship at such high pressure let alone deploy it ashore. Vessels of this pressure range do exist, but they are very heavy and costly. Refrigerated pressure vessels produce huge benefits to the amount of hydrogen that can be stored, especially when the temperature is reduced to below 100K. However to avoid complexity in the support system of the aerostat as well as cost, reliability and maintainability, it was decided that a refrigeration system would not be included in the storage system design. Therefore, pressure alone would dictate the number of ISO tanks required.

After further research it became clear that commercial pressure vessels usually only operated at pressures up to and around 450 bar, such as the Dynetek 450 bar/6527 psi hydrogen Dynecell cylinders (source: www.dynetek.com), primarily due to the danger involved in working at higher pressures. Therefore, with pressure capped at this level and no refrigeration system, the possible number of required ISO tanks is 6 to 8.

After thorough investigation, no ‘off the shelf’ commercial pressure vessel could be found at the necessary capacity and pressure. To further examine their feasibility one

would have to be designed and so preliminary calculations were made to estimate the ISO tank's size and weight.

ISO Tank Design

A spreadsheet was formulated, which calculated pressure vessels sizes using Thin Walled Cylinder theory, as shown below.

$$\sigma = \frac{P \cdot r}{t}$$

σ = Hoop Stress

P = Pressure

r = Inner radius

t = Wall thickness

For the hemispherical ends of the cylinder the following formula was used to calculate axial stress.

$$\alpha = \frac{P \cdot r}{2t}$$

α = Axial Stress

The following two materials were then investigated for use in the ISO tank design:

- Stainless Steel Cold Rolled (AISI Type 302 Stainless Steel, cold rolled to 1550 Mpa tensile strength)
- Titanium Alloy (TIMETAL 3-2.5 Titanium Alloy (Ti-3Al-2.5V; ASTM Grade 9) CWSR))

Both materials have a history of being used in pressure vessel application and a full description can be found in Appendix 5. Calculations were performed to estimate the weight and dimensions of a 460 bar ISO tank using the above materials. It quickly became apparent that these materials produced very heavy pressure vessels in the region of 40 to 80 MT each, due to the high wall thickness required. Therefore they were quickly regarded as unfeasible for this task. Snapshots of the spreadsheets used to form these calculations can be found in Appendix 5.

However, pressure vessels still appeared to be the only viable option for storing, deploying, and quickly releasing the hydrogen required by both the variants of 'recovery' aerostat. Therefore, further investigation was performed into the variety of alternative materials that could be used to carry out this task. Composite materials seemed to represent the most likely solution. They are high strength and low in weight.

Composite Pressure Vessel

Composite pressure vessels are an established technology and are already produced on a small scale by companies such as EDO Fiber Science. These are high

pressure vessels with very limited capacity and are intended to be used as fuel storage tanks on hydrogen powered vehicles. Investigation was performed into any complications arising from scaling up the small pressure vessel to higher storage capacity. EDO Fiber Science and other industries involved were unwilling to divulge information on this subject due to commercial sensitivity.

Material scientists within NSWC Carderock such as were approached for further information. It seems that there are no direct manufacturing issues associated with larger pressure vessels, with the exception of having to produce large inner liners. However, polymer inner liner would be possible and would help to keep the overall weight down. Permeability might be an issue but is an unknown factor without further research. (Extracts of the email conversation with Roger Crane on this issue can be found in Appendix 5)

With the above in mind there was no obvious reason why composite materials could not be used to fulfill this role. Therefore, a suitable composite was found, a spreadsheet was compiled, and calculations were performed to estimate the dimensions and weight of such a vessel. The spreadsheet below details the material used and the results:

Composite Pressure Vessel Design Calculations

Safety Factor (Ref: www.tateandale.com/asme_specs/index.html)	
4	
Pressure (bar)	
460	

Material			
Carbon Fiber Composite (SGL Carbon Group SIGRAFIL C® C30 T045 EPY Continuous Tow Carbon Fiber with 45k filaments, Epoxy Sizing)			

Material Properties			
Density (kg/m ³)	Ultimate Tensile Strength (Pa)	Yield Tensile Strength	Poisson's Ratio
1,800	3.80E+09	Unknown	Unknown

Stresses Experienced (Safety Factor Included in 'Pass' yes or no cell)			
Cylinder Wall Stress			
Hoop Stress	Pass		
889,333,333.3	Yes		
Cylinder End Stress			
Axial Stress	Pass		
444,666,666.7	Yes		

ISO Tank Characteristics (Spherical Ends)			
Inner Radius (m)	Length (m)	t (m)	Volume (approx) (m ³)
1.16	6.1	0.06	25.79
Weight (kg)	Weight of Six (including weight of Hyd) (kg)		
4,925.84	32,523.53		

Table 7: Composite Pressure Vessel Spreadsheet

The spreadsheet incorporated a safety factor of 4 as is standard in the manufacturing of pressure vessels (source: ASME Specs, www.tateandale.com/asme_specs/index.html). Without knowing the actual yield tensile strength of the material, the ultimate tensile strength was used in its place. This was deemed prudent considering the high safety factor already being used. Therefore the hoop and axial stresses calculated had to be 4 times less than the materials ultimate tensile strength. This produced an ISO tank with the above dimensions and weight.

Number of ISO Tanks Required to be Deployed

To fill the 40 MT balloon to its maximum payload, 41,149 m³ of hydrogen is required. To fill the 70 MT balloon to its maximum payload, 68,567 m³ is required. The following number of composite ISO tanks will need to be deployed in each case.

Each ISO tank has the capability of carrying the following amount of normalized hydrogen (sea level state):

$$\begin{aligned}
 \text{Volume of Hydrogen} &= \text{Pressure (bar)} * \text{ISO Tank Volume} \\
 &= 460 * 25.79 \\
 &= 11,863.4 \text{ m}^3
 \end{aligned}$$

Balloon - 40 MT Payload

$$\begin{aligned}\text{Number of ISO tanks} &= \text{Required volume} / (\text{Pressure (bar)} * \text{ISO Tank Volume}) \\ &= 41149 / (460 * 25.79) \\ &= 3.47 \Rightarrow 4 \text{ ISO tanks}\end{aligned}$$

Balloon - 70 MT Payload

$$\begin{aligned}\text{Number of ISO tanks} &= 68567 / (460 * 25.79) \\ &= 5.78 \Rightarrow 6 \text{ ISO tanks}\end{aligned}$$

The weight of each ISO tank is 4,925 kg. Therefore a CH-53 with a maximum lifting capacity of 16,000 kg would require two journeys to deploy the amount of gas required for the 40 MT balloon and would require 3 runs to deploy for the 70 MT balloon (if hydrogen gas weight of 3 MT is included, see above spreadsheet).

Hydrogen Production

It would be preferred if hydrogen was not stored in a high pressure vessel for long periods onboard a ship in transit. To prevent this problem, a method of hydrogen production is available at the Sea Base. Also after a mission is completed, ideally the spent ISO tanks would then be available to be re-filled to be ready for the next mission.

There are various methods of hydrogen production. The most established, light and portable method, which is viable for this task is electrolysis.

Electrolysis

Various companies such as Hydrogenics Corporation produce portable on-site electrolysis units, which only require fresh water and power to operate.



Figure 37: Hydrogenics Electrolysis Generators (inc ISO Container Version)

The HySTAT-A shown above is a scalable system capable of producing up to 120 Nm³/h of 99.5% pure hydrogen. These generators come in a range of sizes up to and including 40' ISO containers. Compressors are also available from the company that raise pressure to the region of the required 450 bar. The large-scale production units require approximately 4.2 kWh/Nm³. Therefore a 120 Nm³/h generator working at full capacity would consume roughly 504 kW/h. An average container ship or transport ship produces roughly 1 MW/h of electrical supply. Therefore this power consumption would be a huge burden on any ship and would only be able to support one to two units. Further information on these units can be found in Appendix 6.

Therefore, the production rates may be too small, as they would be capped at a maximum of 120 Nm³/h. The following calculations were made to determine the time required to produce the necessary volumes of hydrogen.

Balloon - 40 MT Payload

Production Time = Volume of hydrogen required / Production rate

$$\begin{aligned} &= 41150 / 120 = 342.9 \text{ hrs} \\ &= 14.2 \text{ days} \end{aligned}$$

Balloon - 70 MT Payload

$$\text{Production Time} = 68567 / 120 = 571.4 \text{ hrs} = 23.8 \text{ days}$$

The production times of 14 to 24 days are long lag time when the balloon would ideally be deployed in short notice. This method of hydrogen production is established and can be acquired as an “off-the-shelf” item; multiple units could be acquired to increase the production rate. However, a quicker method of production would be preferred and so other techniques were pursued.

Established Steam Reforming

Steam reforming or hydrogen reforming is a method of producing hydrogen from hydrocarbons. On an industrial scale, it is the dominant method for producing hydrogen. However, these plants are expansive units, which require a large area of land to operate in. These plants are too heavy and cumbersome to operate within a ship.

Companies such as ‘Mahler Advanced Gas Systems’ produce various small and medium sized reforming plants and claim to have production rates of up to 10,000 Nm³/h. Below is a flow diagram of their plant system and is a good example of how medium scale hydrogen reforming operates.

- 1: Feed compression unit
- 2: Feed pretreatment
- 3: Reforming and steam generation
- 4: High temperature conversion

- 5: Heat exchanger unit
- 6: Pretreatment of boiler feed water
- 7: Purification unit - HYDROSWING® system

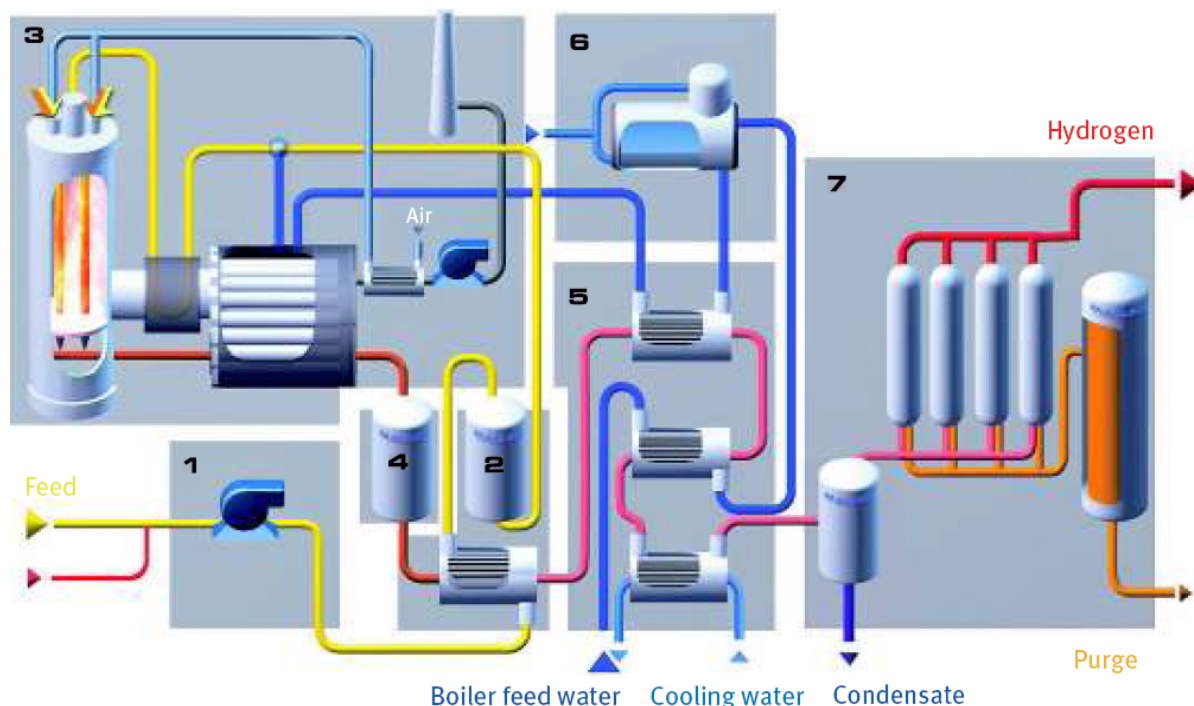


Figure 38: Hydrogen Reforming Process

This system uses hydrocarbons as its feedstock. To transport large amounts of the hydrocarbons commonly used to feed this system such as LPG or Naphtha would be costly and require large amounts of space. However, an abundant hydrocarbon within Navy vessels that is already in place is the NATO F-76 diesel fuel used to power its engines. Mahler were approached with an enquiry to question whether NATO F-76 could be used as a feedstock in their reforming plants. They replied:

“We have worked on NATO projects earlier [in the year] and it turned out that these hydrocarbons [NATO F-76] are very difficult (or almost impossible) to be handled in the steam reforming process. We can only offer H₂ generation based on Natural Gas, LPG or Naphtha).”

It was also remarked that these on-site plants could not be transported due to their size (24 x 18m, height 15m). It is clear that no established and proven steam reforming plant exists small, transportable, and uses diesel as its feedstock.

Future Steam Reforming ‘Under Research’

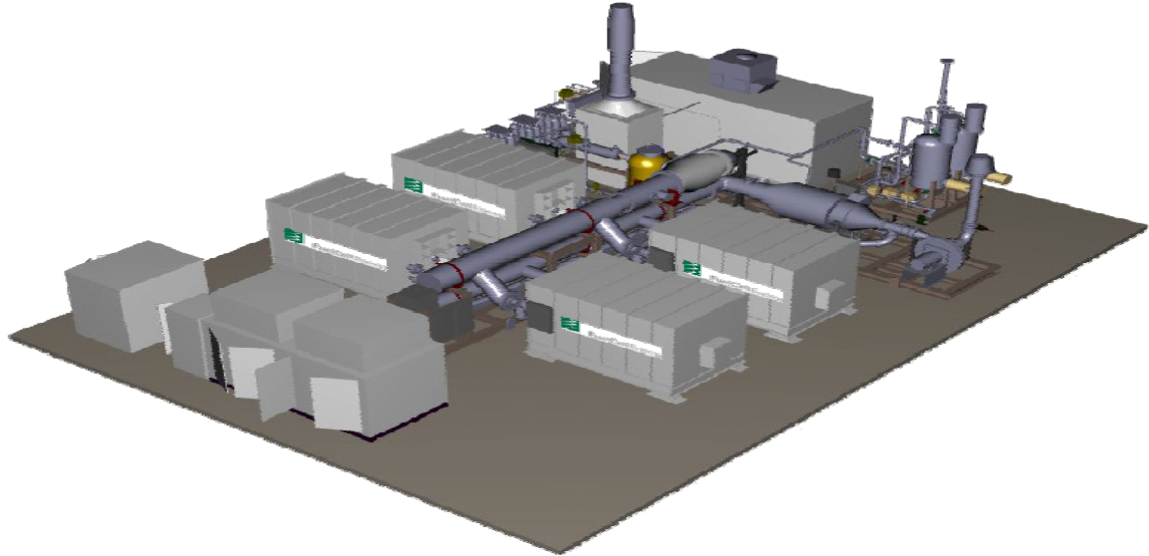
Small-scale reforming units are currently subject to scientific research as a way to provide hydrogen to fuel cells. Research and early development exists in the use of Navy F-76 Diesel fuel as their feedstock. FuelCell Energy Inc lead the way in this research and are currently under contract with ONR (Office of Naval Research) to produce ‘Fuel Cell Power Plant Development’ based on DFC (Direct Carbonate Fuel Cell) technology,

utilizing U.S. Navy logistic fuels. Various papers have been written on this subject as well as one investigating the co-production of electricity and hydrogen. A selection of these paper's titles are below. Their abstracts have been included in Appendix 7.

- 'Distillate Fuel Processing for Marine Fuel Cell Applications' – G. Steinfeld, R. Sanderson – Unpublished, prepared for presentation at the AIChE Spring 2000 Meeting.
- 'Demonstration of a Fuel Cell Power Plant for Co-production of Electricity and Hydrogen' – FuelCell Energy Inc.
- 'SHIPS SERVICE FUEL CELL POWER PLANT DEVELOPMENT' – FuelCell Energy Inc.

These papers discuss the use of DFC Fuel Cell in the production of electricity and hydrogen from Navy diesel. The Co-production of Electricity and Hydrogen paper claims to be able to produce up to 1,200 lbs of hydrogen per day using a power plant similar to the one shown below.

DFC1500MA



OVERALL LAYOUT AND ACCESS SPACE

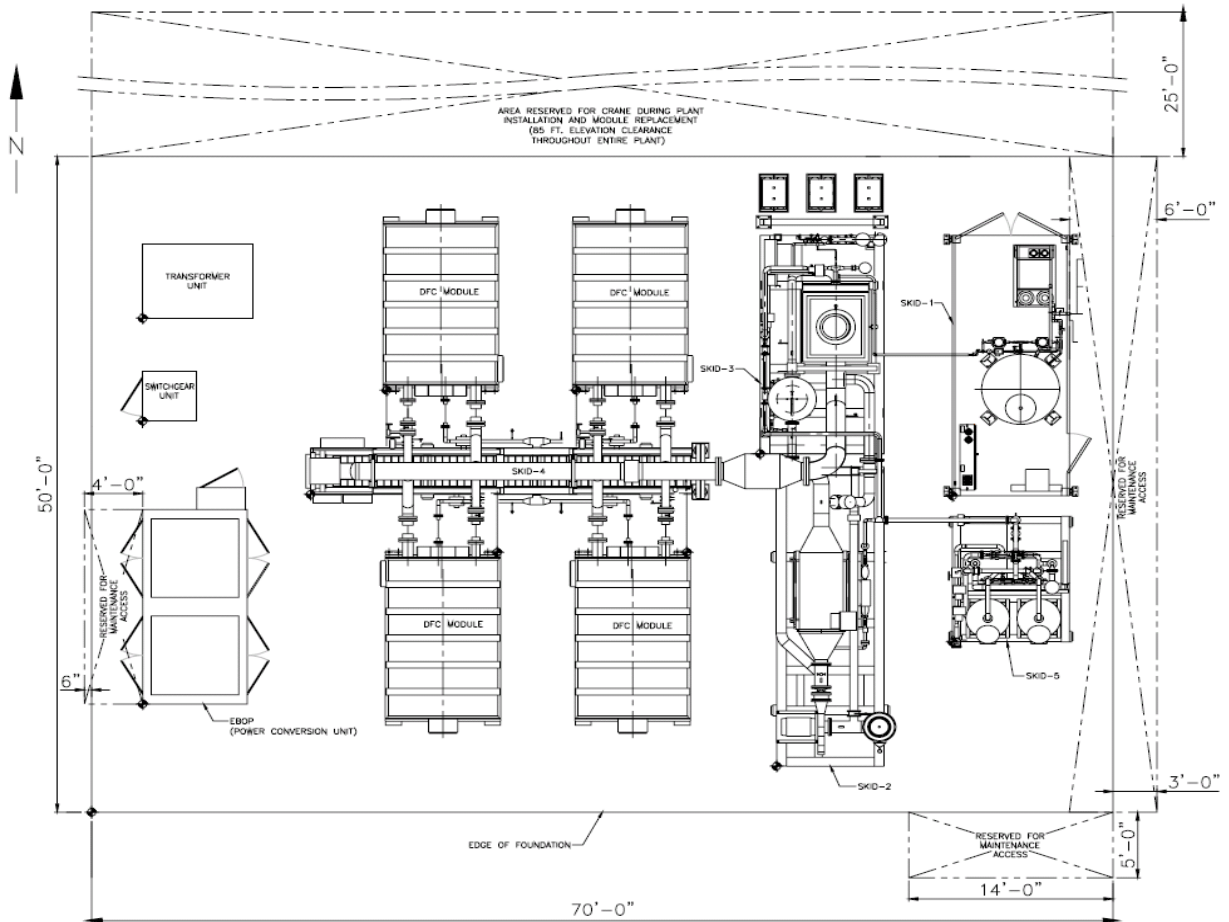


Figure 39: FuelCell Energy DFC1500MA

It is suggested in the other papers that this fuel cell could be adapted to take NATO F-76 as its feedstock. Its general characteristics are:

Layout Width = 15.24 m (50 ft)

Layout Length = 21.34 m (70 ft)

Hydrogen Produced = 544.31 kg/day (1,200 lbs/day)

Power Output = 1,000 kW

To produce the amount of hydrogen required, the DFC hydrogen plant would have to be running for the following duration.

Production Time for Balloon - 40 MT Payload

$$\begin{aligned} \text{Number of Moles Required} &= (\text{Pressure} \times \text{Volume}) / (\text{R} \times \text{Temp}) \\ &= (101,300 \times 41,150) / (8.2058 \times 288) = 1,763,867 \text{ moles} \end{aligned}$$

1 Hyd Mole = 2.016 grams

Therefore Total Mass Required = $1,763,867 \times 0.002016 = 3,555.96 \text{ kg}$

Production Time = Mass required / Production rate
 $= 3,555.96 / 544.31 = 6.53 \text{ days}$

Production Time for Balloon - 70 MT Payload

Production Time = $5,925.21 / 544.31 = 10.89 \text{ days}$

Amount of Fuel Required

Hydrogen roughly makes up 13.23% of the mass of Nato F-76 therefore the amount of diesel required to fill the 40 MT payload balloon is as follow.

Mass of fuel required = (Mass of Hydrogen/Mass Percentage) * 100
 $= (3,555.96/13.23) \times 100 = 26,878 \text{ kg}$

Volume of fuel = Mass/density (kg/m^3) = $26,878/852 = 31.55 \text{ m}^3 = 8334.63 \text{ US Gallons}$

With layout configuration changes, the DFC1500MA could fit onto the cargo area of a large logistics ship but it would take up a considerable proportion of the ship's hold. As shown, it still takes a considerable amount of time to generate the hydrogen required and consumes an enormous amount of fuel at over 8,300 gallons just to fill the smaller 40 MT payload balloon. It would also need considerable maintenance to keep it running over long periods of time.

Hydrogen Production Conclusion

After comparing the two hydrogen generation methods, electrolysis and steam reforming, it was determined that neither would be an ideal solution for the proposed role. Each method takes a considerable amount of time to generate the hydrogen required. Electrolysis may be the most suitable option to meet the necessary requirements based on the following reasons:

- The one 40 ft ISO container it requires takes up considerably less room than the steam reforming plant.
- It consumes large amounts of energy (0.5 MW/h) but this is comparable to the 8,334.63 gallons of fuel consumed by the steam generation unit.
- The electrolysis unit comes as a compact ready to run unit that would take little set up time.

If steam reforming methods improve in the near future, it may be a more viable option for ship bound hydrogen generation.

Method of Operation

Now that the complete architecture of the ‘recovery’ aerostat has been explained, a ‘Method of Operation’ or ‘modus operandi’ can be constructed. The following describes a possible ‘Method of Operation’.

1. Deploy a hydrogen generation unit, hydrogen ISO storage tanks and multiple packs of both variants of the balloon, on-board a U.S. Navy logistics vessel in a cargo hold or deck that is easily accessible by both crane and helicopter.
2. Fill up the hydrogen tanks on route to the destination.
3. When a disabled military vehicle has been identified, helicopters will pick up the aerostat balloon pack required (40 or 70 MT max) and however many ISO tanks are required to complete the operation.
4. 16 to 40 MT payload would require 1-4 ISO tanks
5. 40 to 70 MT payload would require 4-6 ISO tanks

Simple calculations can be carried out to identify how much gas is required based on vehicle type and its mission configuration.

6. Each CH-53 would be able to carry either 2 ISO tanks and aerostat pack or 3 ISO tanks, which is an optimistic estimation based on 3 ISO tanks = approx 15 MT
However this weight could easily increase with design additions.

40 MT Payload Balloon would require a maximum of 2 helicopter runs.
70 MT Payload Balloon would require a maximum of 3 helicopter runs.

7. Deploy equipment to area of deployment.
8. Attach rigging to the military vehicle.
9. Attach ‘auto-release’ sandbags to the vehicle.
10. Attach the vehicle to ground anchor points.
11. Semi-inflate the balloon collar.
12. Fill aerostat through the ‘inflation’ pipe.
13. Hold out excess aerostat envelope as a skirt to provide friction to balloon collar.
14. Fill until vehicle is lifted off the ground.
15. Over-fill the balloon.
16. Fully inflate the balloon collar until it has clamped securely.

- 17.** Attach towing lines to the helicopter.
- 18.** Release ground anchors.
- 19.** Reach a safe altitude (500-1,000ft) then release hydrogen through the solenoid valves until an equilibrium has been reached.
- 20.** To increase altitude, if required, release as many sandbags as necessary.
- 21.** Tow balloon back to the Sea Base.
- 22.** Anchor balloon to the ship cargo area and release the damaged vehicle for repair.
- 23.** Keep the balloon inflated for future near term missions or deflate through the solenoid valves and re-package.

Design description

As discussed earlier in the report, the concept has evolved into two variants due to the extra cost and support equipment required to reach up to a payload capacity sufficient to lift a M1A1 Main Battle Tank. A design description for both variants of aerostat is described below.

Balloon - 40 MT Max Payload

This 'recovery' aerostat variant has the following main characteristics.

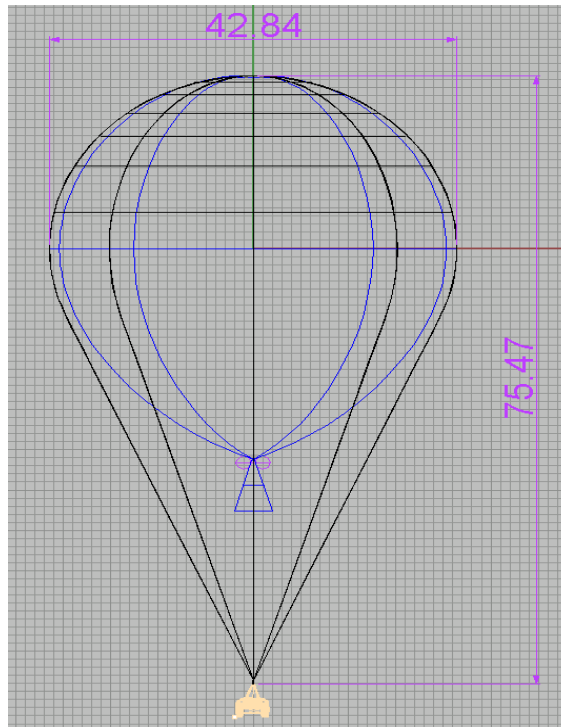


Figure 40: Technical Drawing - 40MT Payload Balloon

Max Payload = 40 MT

Max Diameter = 42.83 m

Max Volume = 41,150 m³

Aerostat Mass = 5,265 kg

Envelope Material = ILC Dover vinyl coated polyester laminate

Envelope Surface Area = 5,764 m²

Type of Balloon Rigging = L&SS Fiber Core (D=13mm)

Length of Balloon Rigging = 847.78 m

Payload Shackle = I&I Slingmax 85MT Bolt Type

Payload Rigging = I&I Slingmax Slings (Standard U.S. Armed Forces Inventory)

Towing Configuration = MH-53E Sea Dragon

Towing Speed = 45 knots Steady State, 55 knots Surge

Method of inflation = Piping attached to the top of the interior of the balloon, running out through the neck of the balloon.

Method of deflation = Solenoid valves located at the top of the balloon

Maintaining its Shape = Balloon collar clamped around the balloon's neck.

Filling Procedure = Hydrogen stored and released from 1-4 deployable 5 MT composite ISO tanks.

Source of Hydrogen = ISO tank re-filled from Hydrogenics Corporation HyStat-A Electrolysis hydrogen plants requiring 504 kW/h (120 Nm³/h).

Hydrogen Production time for max payload = 14 days

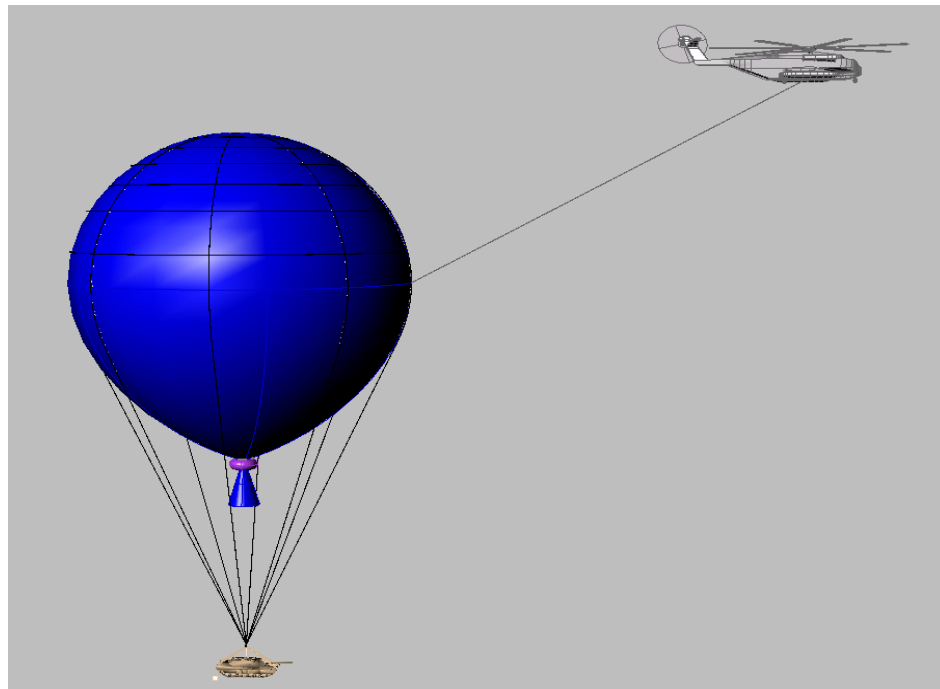


Figure 41: Towing 40MT Payload Balloon

Balloon - 70 MT Max Payload

This 'recovery' aerostat variant has the following main characteristics.

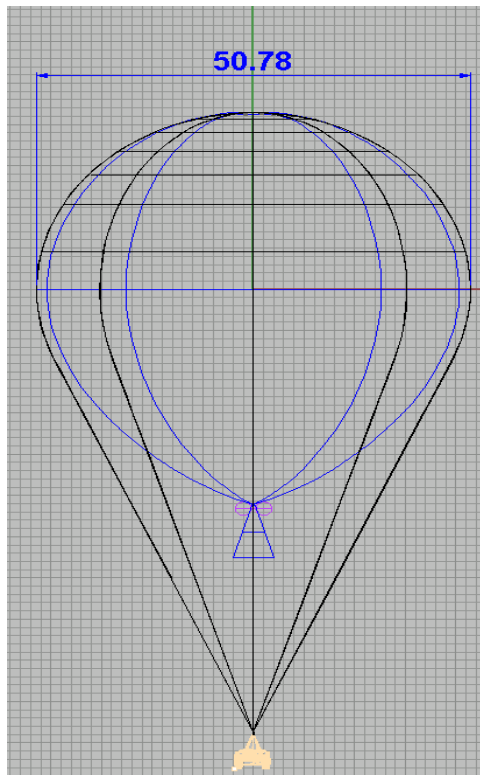


Figure 42: Technical Drawing - 70 MT Payload Balloon

Max Payload = 70 MT

Max Diameter = 50.78 m

Max Volume = 68,567 m³

Aerostat Mass = 5,424 kg

Envelope Material = ILC Dover vinyl or urethane coated high modulus laminate

Envelope Surface Area = 8,101.44 m²

Type of Balloon Rigging = L&SS Fiber Core (D=18mm)

Length of Balloon Rigging = 1,005.07 m

Payload Shackle = I&I Slingmax 85MT Bolt Type

Payload Rigging = I&I Slingmax Slings (Standard U.S. Armed Forces Inventory)

Towing Configuration = MH-53E Sea Dragon

Towing Speed = 35 knots Steady State, 45 knots Surge

Method of inflation = Piping attached to the top of the interior of the balloon, running out through the neck of the balloon.

Method of deflation = Solenoid valves located at the top of the balloon

Maintaining its Shape = Through a balloon collar clamped around the balloon's neck.

Filling Procedure = Hydrogen stored and released from 4-6 deployable 5 MT composite ISO tanks.

Source of Hydrogen = ISO tank re-filled from Hydrogenics Corporation HyStat-A Electrolysis hydrogen plants requiring 504 kW/h (120 Nm³/h).

Hydrogen Production time for max payload = 24 days

Aerodynamic Properties

The 'recovery' aerostats are to be towed by the CH-53 helicopter and its variants. The only helicopter with experience in towing heavy equipment is the CH-53 variant the MH-53E Sea Dragon. Figure 42 shows one of their capabilities, towing a sonar array to detect and destroy mines.



Figure 43: MH-53E Towing a Sonar Array Sled

This results in a source of towing characteristics for this helicopter. The towline and mounting points have the following maximum tension loads.

Condition	Max Load (lbs)	Max Load (kg)
Steady State	25,000	11,340
Surge	40,000	18,144

Table 8: MH-53E Tow Tension Max Loads (Source: National Defense Magazine, www.nationaldefensemagazine.org)

Knowing maximum loading conditions and if the aerodynamic drag on the balloons can be deduced, then a maximum transit speed can be identified.

A spreadsheet was formulated for both the 40 MT and 70 MT max payload balloons. Identical methodologies were followed for each. All formulae and data were sourced from; 'Engineering Aerodynamics' by Walter Stuart Diehl.

Balloon - 40 MT Max Payload

The aerodynamic drag of an object can be calculated as:

$$F_D = q \cdot A_{ref} \cdot C_D$$

Where;

$$F_D = \text{Drag (kg)}$$

$$q = \text{Dynamic Pressure}$$

$$A_{ref} = \text{Projected (Cross Sectional) Area}$$

$$C_D = \text{Coefficient of Drag}$$

For a spherical aerostat,

$$A_{ref} = \pi R^2$$

As this balloon will primarily operating at low altitudes the dynamic pressure is standard sea level and can be calculated as follows. If the balloon were to operate at higher altitudes its aerodynamic drag properties would improve not worsen.

$$q_o = \text{Standard Dynamic Pressure}$$

$$q_o = 0.0625 \cdot V^2$$

$$\text{Where; } V^2 = \text{Velocity (m/s)}$$

Drag on the Balloon Sphere

There is a lack of published data on the aerodynamic properties of large spheres with high Reynolds (Re) numbers, probably due to the lack of large wind tunnels capable

of performing these kinds of tests. However, in order to continue the drag calculation, a coefficient of drag was deduced from a graph in 'Engineering Aerodynamics' by Walter Stuart Diehl p.263. A Co-efficient of Drag of 0.2 will be used in all sphere drag calculations and is accurate enough for the purposes of drag estimation. A spreadsheet was formulated with varying wind speeds and outputted the following results.

Balloon Drag						
Wind Speed (kts)	Speed (m/s)	Standard Dynamic Pressure	Balloon Radius	Projected Area	Coefficient of Drag	Drag (kg) at 0 ft ISA
0.00	0.00	0.00	21.42	1,441.02	0.20	0.00
5.00	2.57	0.41	21.42	1,441.02	0.20	119.34
10.00	5.15	1.66	21.42	1,441.02	0.20	477.36
15.00	7.72	3.73	21.42	1,441.02	0.20	1,074.05
20.00	10.30	6.63	21.42	1,441.02	0.20	1,909.42
25.00	12.87	10.35	21.42	1,441.02	0.20	2,983.48
30.00	15.44	14.91	21.42	1,441.02	0.20	4,296.21
35.00	18.02	20.29	21.42	1,441.02	0.20	5,847.61
40.00	20.59	26.50	21.42	1,441.02	0.20	7,637.70
45.00	23.17	33.54	21.42	1,441.02	0.20	9,666.46
50.00	25.74	41.41	21.42	1,441.02	0.20	11,933.90
55.00	28.31	50.10	21.42	1,441.02	0.20	14,440.02
60.00	30.89	59.63	21.42	1,441.02	0.20	17,184.82
65.00	33.46	69.98	21.42	1,441.02	0.20	20,168.30
70.00	36.04	81.16	21.42	1,441.02	0.20	23,390.45

Table 9: Aerodynamic Drag Calculations for 40 MT Balloon Sphere

Drag on the Vehicle Payload

The largest vehicle was selected as representative of the vehicle payload. It would be treated pessimistically as a squared cylinder with a coefficient of drag of 2.0. The largest vehicle to be lifted by this balloon would be the M2A3 Bradley Fighting Vehicle with a height of 2.97 m and width of 3.20 m. These dimensions can be used to estimate the vehicle's projected area. A spreadsheet was formulated and produced the following results:

Vehicle Drag (M2A3, Treated as a square cylinder)						
				M2A3 Bradley Fighting Vehicle		
Wind Speed (kts)	Speed (m/s)	Standard Dynamic Pressure	Max Width	Max Height	Projected Area	Drag (kg) at 0 ft ISA
0.00	0.00	0.00	3.20	2.97	9.50	0.00
5.00	2.57	0.41	3.20	2.97	9.50	7.87
10.00	5.15	1.66	3.20	2.97	9.50	31.48
15.00	7.72	3.73	3.20	2.97	9.50	70.84
20.00	10.30	6.63	3.20	2.97	9.50	125.93
25.00	12.87	10.35	3.20	2.97	9.50	196.77

30.00	15.44	14.91	3.20	2.97	9.50	2.00	283.35
35.00	18.02	20.29	3.20	2.97	9.50	2.00	385.67
40.00	20.59	26.50	3.20	2.97	9.50	2.00	503.73
45.00	23.17	33.54	3.20	2.97	9.50	2.00	637.53
50.00	25.74	41.41	3.20	2.97	9.50	2.00	787.08
55.00	28.31	50.10	3.20	2.97	9.50	2.00	952.37
60.00	30.89	59.63	3.20	2.97	9.50	2.00	1,133.39
65.00	33.46	69.98	3.20	2.97	9.50	2.00	1,330.16
70.00	36.04	81.16	3.20	2.97	9.50	2.00	1,542.67

Table 10: Vehicle Drag Calculations for 40 MT Payload Balloon

Drag on the Rigging

The drag due to the rigging lines can be calculated using the following derivation of the general drag formula where the coefficient of drag is 1.10.

$$F_D = C_D \cdot q \cdot D \cdot L$$

Where;

D = Diameter of the Rigging

L = Length of the Rigging

Drag due to Rigging						
Wind Speed (kts)	Speed (m/s)	Standard Dynamic Pressure	Diameter	Length	Coefficient of Drag	Drag (kg) at 0 ft ISA
0.00	0.00	0.00	0.013	847.78	1.10	0.00
5.00	2.57	0.41	0.013	847.78	1.10	5.02
10.00	5.15	1.66	0.013	847.78	1.10	20.08
15.00	7.72	3.73	0.013	847.78	1.10	45.18
20.00	10.30	6.63	0.013	847.78	1.10	80.32
25.00	12.87	10.35	0.013	847.78	1.10	125.50
30.00	15.44	14.91	0.013	847.78	1.10	180.72
35.00	18.02	20.29	0.013	847.78	1.10	245.98
40.00	20.59	26.50	0.013	847.78	1.10	321.28
45.00	23.17	33.54	0.013	847.78	1.10	406.62
50.00	25.74	41.41	0.013	847.78	1.10	501.99
55.00	28.31	50.10	0.013	847.78	1.10	607.41
60.00	30.89	59.63	0.013	847.78	1.10	722.87
65.00	33.46	69.98	0.013	847.78	1.10	848.37
70.00	36.04	81.16	0.013	847.78	1.10	983.91

Table 11: Drag Calculations for 40 MT Payload Balloon Rigging

Now that the drag on the main components of the aerostat has been identified, the total tension on the towline can be calculated using the following formula.

$$Tension = \sqrt{(D_{sphere} + D_{payload} + D_{rigging})^2 + VerticalDrag^2}$$

Where;

VerticalDrag = Drag induced vertically on the balloon due to vertical gusts of wind

After consulting with engineers with experience on the CL75, an assumption has been made that the 40 MT max payload balloon, within temperate weather conditions, will see no more than 2,500 kg of load due to vertical gusts. With this in mind, the following spreadsheet was compiled to calculate the tension on the toelines at various wind speeds. This was then used to identify the maximum operating steady state and surge flight speeds of the aerostat.

Tow Line Tension										
							(25,000 lbs)		(40,000 lbs)	
Wind Speed (kts)	Speed (m/s)	Heaviness (kg)	Sphere Drag	Vehicle Drag	Rigging Drag	Total Tension	Max Steady State	Pass	Max Surge	Pass
0.00	0.00	2,500.00	0.00	0.00	0.00	2,500.00	11,339.80	Yes	18,143.70	Yes
5.00	2.57	2,500.00	119.34	7.87	5.02	2,503.49	11,339.80	Yes	18,143.70	Yes
10.00	5.15	2,500.00	477.36	31.48	20.08	2,555.34	11,339.80	Yes	18,143.70	Yes
15.00	7.72	2,500.00	1,074.05	70.84	45.18	2,768.80	11,339.80	Yes	18,143.70	Yes
20.00	10.30	2,500.00	1,909.42	125.93	80.32	3,275.07	11,339.80	Yes	18,143.70	Yes
25.00	12.87	2,500.00	2,983.48	196.77	125.50	4,144.63	11,339.80	Yes	18,143.70	Yes
30.00	15.44	2,500.00	4,296.21	283.35	180.72	5,376.82	11,339.80	Yes	18,143.70	Yes
35.00	18.02	2,500.00	5,847.61	385.67	245.98	6,944.84	11,339.80	Yes	18,143.70	Yes
40.00	20.59	2,500.00	7,637.70	503.73	321.28	8,824.25	11,339.80	Yes	18,143.70	Yes
45.00	23.17	2,500.00	9,666.46	637.53	406.62	10,998.51	11,339.80	Yes	18,143.70	Yes
50.00	25.74	2,500.00	11,933.90	787.08	501.99	13,457.23	11,339.80	No	18,143.70	Yes
55.00	28.31	2,500.00	14,440.02	952.37	607.41	16,193.94	11,339.80	No	18,143.70	Yes
60.00	30.89	2,500.00	17,184.82	1,133.39	722.87	19,204.50	11,339.80	No	18,143.70	No
65.00	33.46	2,500.00	20,168.30	1,330.16	848.37	22,486.24	11,339.80	No	18,143.70	No
70.00	36.04	2,500.00	23,390.45	1,542.67	983.91	26,037.33	11,339.80	No	18,143.70	No

Table 12: Tow Line Tension Calculations for 40 MT Payload Balloon

It can be seen that the maximum operating flight speeds of the 40 MT max payload balloon are as follows:

Max Steady State Speed	45 Knots
Max Surge Speed	55 Knots

Table 13: Operating Speeds for 40 MT Max Payload Balloon

This balloon can operate, when towed by the MH-53 helicopter, at speed of 45 knots. It can then surge up to speed of 55 knots if required.

Balloon - 70 MT Max Payload

An identical methodology was used in the analysis of the 70 MT balloon as was used in the analysis of the 40 MT balloon. The only difference being that a larger assumed vertical drag load of 3,500 kg was used instead of 2,500 kg. Spreadsheets were compiled and produced the following results.

Tow Line Tension										
							(25,000 lbs)		(40,000 lbs)	
Wind Speed (kts)	Speed (m/s)	Heaviness (kg)	Sphere Drag	Vehicle Drag	Rigging Drag	Total Tension	Max Steadt State	Pass	Max Surge	Pass
0.00	0.00	3,500.00	0.00	0.00	0.00	3,500.00	11,339.80	Yes	18,143.70	Yes
5.00	2.57	3,500.00	167.73	7.40	8.24	3,504.80	11,339.80	Yes	18,143.70	Yes
10.00	5.15	3,500.00	670.93	29.58	32.96	3,576.03	11,339.80	Yes	18,143.70	Yes
15.00	7.72	3,500.00	1,509.58	66.56	74.16	3,869.56	11,339.80	Yes	18,143.70	Yes
20.00	10.30	3,500.00	2,683.70	118.33	131.85	4,567.02	11,339.80	Yes	18,143.70	Yes
25.00	12.87	3,500.00	4,193.28	184.89	206.01	5,767.56	11,339.80	Yes	18,143.70	Yes
30.00	15.44	3,500.00	6,038.33	266.25	296.65	7,471.69	11,339.80	Yes	18,143.70	Yes
35.00	18.02	3,500.00	8,218.84	362.39	403.78	9,642.63	11,339.80	Yes	18,143.70	Yes
40.00	20.59	3,500.00	10,734.81	473.33	527.38	12,246.32	11,339.80	No	18,143.70	Yes
45.00	23.17	3,500.00	13,586.24	599.06	667.47	15,259.57	11,339.80	No	18,143.70	Yes
50.00	25.74	3,500.00	16,773.14	739.58	824.03	18,667.78	11,339.80	No	18,143.70	No
55.00	28.31	3500.00	20,295.49	894.89	997.08	22,461.82	11,339.80	No	18,143.70	No
60.00	30.89	3,500.00	24,153.32	1,064.99	1,186.61	26,635.87	11,339.80	No	18,143.70	No
65.00	33.46	3500.00	28,346.60	1,249.88	1,392.61	31,186.12	11,339.80	No	18,143.70	No
70.00	36.04	3,500.00	32,875.35	1,449.57	1,615.10	36,110.04	11,339.80	No	18,143.70	No

Table 14: Tow Line Tension Calculations 70 MT Payload Balloon

As can be seen the maximum operating flight speeds of the 40 MT max payload balloon are as follows:

Max Steady State Speed	35 Knots
Max Surge Speed	45 Knots

Table 15: Operating Speeds for 70 MT Max Payload Balloon

Therefore this balloon can operate, when towed by the MH-53 helicopter at speed of 35 knots. It can then surge up to speed of 45 knots if required. This is significantly lower than the 40 MT max payload balloon and might affect its feasibility as a 'recovery' aerostat depending on operational requirements.

Stress Analysis

Due to insufficient data being available on the envelope material strength properties, it was difficult to perform any in-depth stress analysis. Therefore, the correct material was selected for the specific load it would carrying on the advice of ILC Dover.

However, CargoLifter 75 proved, with a material of similar construction to the two used in this report, that the envelope can easily support loads of a very high magnitude.

Cost of the System

The following areas account for the majority of cost for the system:

- Cost of the balloon envelope
- Cost of fuel consumed to generate the required hydrogen
- Cost of deploying several helicopter runs to the area of deployment
- Purchasing cost of hydrogen generation and storage units

Cost of the balloon envelope

An approximate cost for the balloon envelope of each variant of the balloon has been estimated using the following formula.

Envelope Cost = Balloon Surface Area * Cost (\$) per sq m

40 MT Max Payload Balloon

Envelope Cost = 5,764.09 * 7.20 = \$41,501.43

70 MT Max Payload Balloon

Envelope Cost = 8,101.44 * 24.00 = \$19,4434.62

Cost of Fuel Consumed

The hydrogen generator requires 504 kW/h of power. It is difficult to estimate to total amount of fuel consumed to generate this power output. Due to this difficulty and time restrictions in completing this report, a definite cost figure could not be identified.

Cost of Helicopter Deployment

There are many hidden costs involved in deploying helicopter to areas of operation, and it is not as simple as identifying how much fuel they would burn on each run. At the time the report was completed, no reliable cost figures had been identified for the cost of a MH-53E helicopter per hour of use.

Purchasing Cost of Hydrogen Generation and Storage Units

Unfortunately at the time this report was completed, no cost figures could be obtained from the Hydrogenics Corporation who manufactured the generation units.

Due to the large composite pressure vessels being a future concept and not existing as a 'off the shelf' item for purchase, it is difficult, without considerable time and effort, to estimate the cost of each unit.

Cost Comparison

For the 'recovery' aerostats to be cost effective their cost per deployment needs to be significantly lower than the unit cost of the vehicle they are recovering. Therefore, two examples were taken from the range of vehicles each balloon could potentially recover (source: www.fas.org)

Balloon - 40 MT Max Payload

M2A3 Bradley Fighting Vehicle

Average Unit Cost = \$3,166,000

Balloon - 70 MT Max Payload

M1A1 Abraham Main Battle Tank

Average Unit Replacement Cost = \$4,300,000

It is difficult to carry out a cost comparison without a definite system cost or cost per deployment for the 'recovery' aerostat. However the above vehicles do give a good representation of how expensive military vehicles can be and how worthwhile it may be to recover that potential 'lost cost.'

The 70 MT max payload balloon's envelope alone costs over \$190,000 and therefore cannot be deemed as being 'disposable'. When the balloon returns to the Sea Base, it should either be re-packaged or remain inflated until the next recovery mission.

The 40 MT max payload balloon's envelope has a more reasonable cost of over \$41,000 and therefore could be deemed as disposable especially when compared to the \$3 million vehicle it is recovering. When the time and cost of generating the required hydrogen is considered, it seems less likely that the hydrogen would be wasted and taken up into the atmosphere.

Emergency Breakaway / Failure Scenario

If the balloon experiences moderate to severe weather conditions in-flight, the towing line should be released and solenoid valves activated to ditch the balloon and vehicle into a safe landing area. This is due to the instability of the balloon in high winds.

The balloon should be inflated and deflated at a safe distance. The balloon's envelope is not flammable so if the hydrogen should catch fire, it would burn freely upwards and dissipate into the atmosphere.

Nevertheless, the only reliable method of assessing the dangers posed by the hydrogen filled ‘recovery’ aerostat is to perform design development and vulnerability trials.

Risk Assessment

There are several areas of risk associated with the recovery aerostat concept. There are risks associated with the project’s success, which are primarily concerned with the design of the concept. In addition there are other risks, which could endanger the safety of personnel who would interact with the aerostat. As the design is carried forward, these risks must be minimized or mitigated by focused research and development. Risk identification for the recovery aerostat has been included below.

Project Risk Assessment

Risks to the project’s success with the current concept design. Firstly design severity categories must be established.

Severity	Threat to feasibility of current design
Catastrophic	Design-ending failure.
Disastrous	Major system design overhaul.
Critical	Requires major, but feasible design change
Significant	Requires small change in design
Marginal	Small loss in performance of vehicle no redesign necessary

Table 16: Design Severity Categories

Secondly likelihood categories can be identified.

Likelihood of failure	Description
Very likely	Unproven, untested, theoretical technology. Low confidence in technology.
Likely	Technology is new or under development, questionable and has not been tested.
Possible	Technology is new or under development, but looks promising and has been tested.
Unlikely	Technology is unlikely to fail. Only a slight modification from proven technology.
Proven	Technology is proven or off-the shelf. Failure is remote.

Table 17: Design Likelihood Categories

These tables can then form a risk matrix from which risk assessments can be identified using color-coding for levels of severity.

	Very likely	Likely	Possible	Unlikely	Proven
Catastrophic					
Disastrous					
Critical					
Significant					
Marginal					

Table 18: Design Risk Matrix

Red = Requires Substantial Mitigation, **Orange** = Requires Serious Mitigation, **Yellow** = Requires Mitigation, **Green** = Requires no Mitigation.

The following table assesses various risks and assigns each of them a severity level color.

Item of Concern	Likelihood Of Failure	Severity	Assessment
Composite Pressure Vessel	Likely	Disastrous	
Balloon Collar	Very Likely	Critical	
Balloon Envelope	Unlikely	Disastrous	
Rigging	Unlikely	Significant	
Hydrogen Production	Proven	Disastrous	
Inflation and Deflation Technique	Likely	Catastrophic	
Balloon Towing Technique	Possible	Disastrous	
Short Deployment Time	Very Likely	Disastrous	

Table 19: Design Risk Assessment Table

As can be seen in the above table the main areas of concern with the aerostat concept design are the Composite Pressure Vessels, Balloon Collar and Inflation and Deflation Techniques. These areas demand focused research and development to ensure the design's success if this concept was to be carried forward to the development stage.

Safety Risk Assessment

Safety concerns to personnel with the current design and procedures.

Severity	Harm to Individual or Group at Most Risk from an Accident Sequence
Catastrophic	More than one hundred deaths (large societal risk)
Disastrous	More than ten deaths, up to one hundred deaths
Critical	More than five severe injuries or illness to the individual or group at most risk. Up to ten deaths.
Major	More than five intermediate injuries or illness. Up to five severe injuries or illness
Marginal	More than five minor injuries or minor illness. Up to five severe injuries or illness
Negligible	Up to five minor injuries or minor illness. First-aid medical treatment only

Table 20: Safety Severity Categories

Likelihood Category	Frequency of Occurrence
Frequent	> 0.1/year
Probable	1×10^{-2} to 0.1 /year
Occasional	1×10^{-3} to 1×10^{-2} /year
Remote	1×10^{-4} to 1×10^{-3} /year
Improbable	1×10^{-5} to 1×10^{-4} /year
Highly Improbable	1×10^{-6} to 1×10^{-5} /year
Incredible	$< 10^{-6}$ /year

Table 21: Safety Likelihood Categories

	Frequent	Probable	Occasional	Remote	Improbable	Highly Improbable	Incredible
Catastrophic							
Disastrous							
Critical							
Major							
Marginal							
Negligible							

Table 22: Safety Risk Matrix

Item of Concern	Frequency of Occurrence	Severity	Assessment
Hydrogen Fire In-Tow	Remote	Critical	
Hydrogen Fire During Inflation	Occasional	Major	
Envelope Failure	Improbable	Critical	
Rigging Failure	Improbable	Major	
Hydrogen Production/Storage Fire (on ship)	Disastrous	Remote	
Complete Solenoid Valve Failure	Improbable	Marginal	
Towing Line Failure	Remote	Marginal	
Weapons Fire Damage	Probable	Marginal	

Operator Error	Frequency of Occurrence	Severity	Assessment
Slamming Payload into Side of Ship	Remote	Critical	
Dropping Tank Payload onto the Ground	Occasional	Major	
Damage to Envelope During Loading	Occasional	Major	
Overflow in Hydrogen	Occasional	Critical	
Improper Handling of Pressure Vessels	Occasional	Critical	

Table 23: Safety Risk Assessment Table

As can be seen in the above assessment table, there are many safety risks associated with the unmanned recovery aerostat. These would need to be mitigated if the concept were to evolve further. The risks are primarily associated with fire and operator error. The hydrogen is at its most dangerous when it is being stored within the pressure vessels. These have a high safety factor of 4 to maintain their safety. However, if improperly handled, they could cause a major explosion. Therefore, close attention would need to be paid in mitigating the risk posed by the hydrogen pressure vessels.

If the hydrogen were to burn when at normal (sea level) pressure, it would most likely dissipate into the atmosphere causing minimal damage to personnel. However, the payload would then be left to free-fall down to the ground. This could pose a serious risk to civilian personnel in its flight path. Mapping a route well away from civilian or military personnel could easily mitigate this risk.

High risk is also posed in unloading of the payload in the Sea Base environment. Procedures would have to be in place to mitigate the risk of the payload colliding with sensitive areas of the ship. One such procedure could be the addition of towlines to carefully pull down the aerostat onto a flat cargo area.

Future Direction

If this feasibility study and concept design were to be carried forward, further research and design work needs to be concentrated in the following areas:

- Composite Pressure Vessels for hydrogen storage
- Alternative high efficiency methods of hydrogen production to reduce fuel/power consumption
- In-depth feasibility study and design of the balloon collar to identify whether it could operate as intended
- Cost Analysis of cost per deployment, compared against cost of recovered vehicles
- Inflation procedures
- Identify strength properties of the envelope skin and perform stress analysis of skin due to the payload

Conclusions

This report set out to investigate the feasibility of the use of aerostats in the recovery of damaged military vehicles, in particular main battle tanks such as the M1A1. A capability gap was identified and the most effective aerostat type was selected and advanced forward to the concept design phase. After research and design work, a system was identified that could best suit the needs of the U.S. Navy and Marine Corps.

This concept design consisted of an 'air-crane' type un-powered balloon, which would be towed into and out of operation. It would use hydrogen as its 'lifting gas' and would require an extensive support system to enable it to operate effectively. This system would include hydrogen storage and production facilities.

From the outset, the concept was designed to be as simple and inexpensive as possible to keep cost and maintainability to a minimum. To be cost effective, the aerostat's cost per deployment would have to be significantly lower than the cost of the vehicle it was recovering.

This report has identified several areas of promise in the potential of aerostats for vehicle recovery. For example:

- It has identified that there is an existing airlift capability gap that could be filled with the use of large aerostat.
- They have the potential to lift any vehicle in the Marine Corps and Army inventories.
- A viable system can be constructed where an aerostat can be deployed and retrieve a vehicle back to the Sea Base.
- A cost effective balloon envelope material is readily available, which could support payloads of this magnitude.
- A large aerostat balloon can be towed effectively at reasonable speeds using current MH-53 towing technology.

However, the two variants of the concept, the 40 MT and 70 MT maximum payload balloons, have differing levels of feasibility but share the following common operational and design difficulties that will need to be overcome if the aerostat were to become operational.

- Current on-site hydrogen generation technology such as electrolysis dictates long and costly production times to produce the required amounts of hydrogen.
- A power of 504 kW/h would be placed on the ship when hydrogen was being generated. The 14 – 24 day production time could be reduced, but only by increasing the power burden on the ship even further.
- Hydrogen storage requires heavy, costly and potentially dangerous pressure vessels. To obtain a deployable system, research and development would need to be concentrated on composite pressure vessels which could provide a light and safe storage method.

- The 'Balloon Collar' is an un-proven concept and might need considerable development and re-design work.
- Multiple helicopter flights would be required and therefore occupying valuable Marine and Navy resources.
- The balloon would have a short life. If kept inflated for an extended duration, it would represent a huge radar signature for the Sea Base and would require substantial seawater ballast when deployed on additional missions.
- The inflating of balloons of this size in deployed areas could pose long inflation times and unforeseen problems.

As mentioned, the 70 MT maximum payload balloon shares all these difficulties; however each difficulty is magnified due to its larger size.

This report has demonstrated that the use of aerostats from a Sea Base for the recovery of damaged vehicles ashore is possible but may be unfeasible at this time. The critical piece of technology, which requires development is the composite ISO tank pressure vessel for the storage of high quantities of hydrogen. If an ISO tank can be manufactured with the required capacity and light enough to be deployed by helicopter ashore, then the feasibility of this design would dramatically improve.

The 40 MT maximum payload balloon is the more feasible of the two designs due to its lower volume and low cost envelope skin (\$42,000), which provides improved cost effectiveness. The 70 MT max payload balloon is less feasible due to the long production time for generating the required amount of hydrogen (24 days) and due to the lower cost effectiveness of its expensive envelope skin (\$195,000).

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Appendix

Appendix 1: Evolution of Aerostats

Balloons of various types have a long history dating back to the 2nd and 3rd Centuries AD when China used hot air balloons for military communication.

The first recorded manned flight took place in 1783 in a hot air balloon built by the Montgolfier brothers. The woven cotton fabric balloon reached a height of 500ft carrying one pilot over a distance of 5 ½ miles in 25 minutes. Only a few days later the first manned gas balloon flight took place. Professor Jacques Charles and his co-pilot flew a hydrogen filled balloon to a height of 2000 ft over a distance of 27 miles in two hours.



Figure 44: Model of Montgolfier Brothers Balloon

Aerostats continued to evolve, with various designs flying throughout the 19th century. They were largely attempts to make relatively small balloons more steerable and often contained features found on later airships. These early airships set many of the earliest aviation records. As Aerostat design entered into the 20th century, Airships took the ascendancy. These airships evolved into four distinct categories:

- **Rigid airships** (for example, Zeppelins) had rigid frames containing multiple, non-pressurized gas cells or balloons to provide lift. Rigid airships did not depend on internal pressure to maintain their shape.
- **Non-rigid airships** (blimps) use a pressure level in excess of the surrounding air pressure in order to retain their shape.
- **Semi-rigid airships**, like blimps, require internal pressure to maintain their shape, but have extended, usually articulated keel frames running along the bottom of the envelope to distribute suspension loads into the envelope and allow lower envelope pressures.
- **Hybrid airship** is a general term for an airship that combines the properties of aerodynamic lift and lighter than air technology. The term "hybrid airship" refers to craft that obtains a significant portion of their lift from aerodynamic lift and often require substantial take-off rolls before becoming airborne.

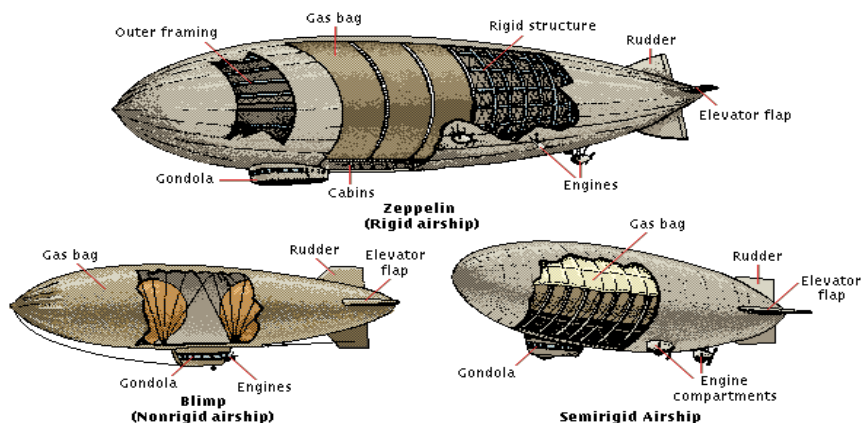


Figure 45: Airship Types

During the early 20th Century Airships were primarily used by the military for long range observations and by commercial companies for the transport of passengers. During the period between the two great wars (1918-1939) many large airships were manufactured such as;

Graf Zeppelin; This German large rigid dirigible flew between 1928 and 1937 with a total length of 236.6 m (776 ft) and volume of 105,000 m³ (3,708,040 ft³). It was powered by 5 Maybach 550 HP engines and could carry a payload of 60 metric tonnes.

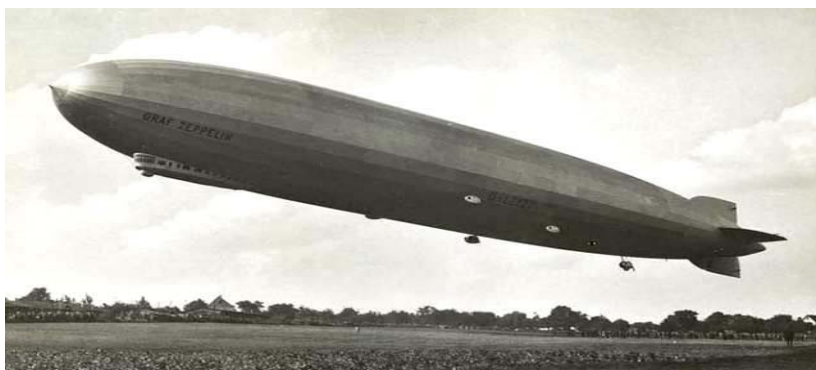


Figure 46: Graf Zeppelin

By the time it was retired, the Graf Zeppelin had made 590 flights, flew more than a million miles and carried 13,110 passengers without a fatality.

R101; The British dirigible took its maiden flight on 4th October 1930, it had a length of 237 m (777 ft) and diameter of 40 m (131 ft). With a volume of 160,00 m³ (5,500,000 ft³) constructed mainly from steel it flew at up to 71 mph.

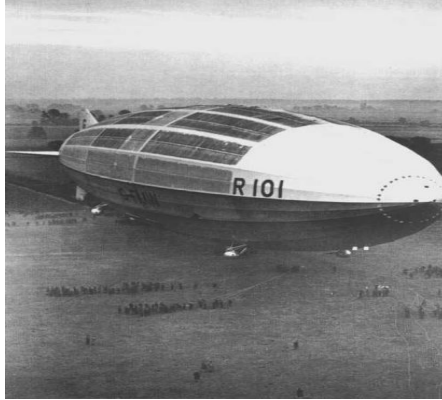


Figure 47: The British R101

During the R101's maiden flight it encountered strong winds over France and its skin was partially ripped from its structure and a gasbag was ruptured causing the aircraft to crash-land. When the engine collided with a gasbag, the Hydrogen ignited resulting in the death of 48 crew members and passengers.

Unfortunately, these craft were extremely sensitive to weather extremes and several were lost in high winds or storms. The extreme weather would force the airship to ground, which usually resulted in the explosion of the Hydrogen gas contained within. These high profile crashes persuaded the U.S. to reconsider the use of Hydrogen gas in their future airships. From 1930 onwards all American Navy Airships were developed with the use of the inert Helium gas.

Photo # NH 44075 Lighter-than-air demonstration at NAS Lakehurst, N.J., circa 1930-1931

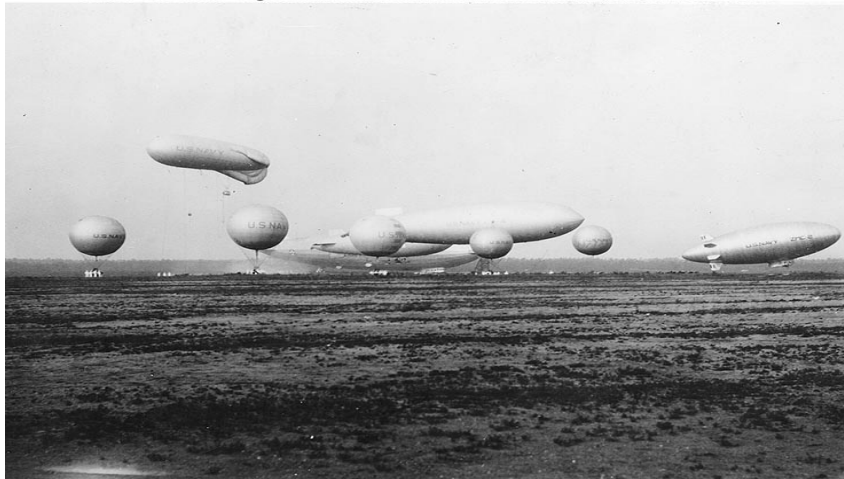


Figure 48: USN Airships circa 1930's

Airships and other aerostats such as hot air balloons are no longer used for passenger transportation but they continued to be used for other purposes such as advertising and sightseeing, such as the Goodyear blimp.

Appendix 2: Army Representative Armored Unit (ARAU) Data

SRC	Model	Qty	Description	L	W	H	W (lbs)	Weight (MT)	Cumulative Weight (MT)
07206G000	M1064A	4	CARRIER 120MM MORTAR	210	106	105	27,635	12.54	50.14
07206G000	M1068A	3	CARRIER ARMD CMD POST	205	100	107	25,650	11.63	34.90
07206G000	M113A3	10	CARRIER PERS FTRAC	210	100	100	23,880	10.83	108.32
07206G000	M577A3	4	CARR CMD POST LTRAC	192	100	109	22,582	10.24	40.97
07206G000	M2A3	1	FIGHTING VEH F/TRACK	258	129	142	64,858	29.42	29.42
07206G000	M7	4	FIRE SPT VEH BRADLEY	258	131	120	59,285	26.89	107.57
07206G000	M3A3	3	FIGHTING VEH F/TRACK	258	142	147	73,272	33.24	99.71
07206G000	PU-798	1	GEN SET DED TLR MTD	135	86	67	2,480	1.12	1.12
07206G000	MK-272	1	INSTL/EQP KIT SHELTER	96	53	108	201	0.09	0.09
07206G000	M121	4	MORTAR 120 MM	95	60	45	720	0.33	1.31
07206G000	M1097A	3	TRK UTIL HVY HMMWV	191	86	72	6,774	3.07	9.22
07206G000	M1A2	1	TK CBT FTRAC 120MM GN	355	144	122	128,679	58.37	58.37
07206G000	M1083A	1	TRK CARGO MTV W/EQP	274	96	112	28,115	12.75	12.75
07206G000	M1078A	1	TRK CARGO LMTV W/EQP	253	96	112	21,756	9.87	9.87
07206G000	M1078A	1	TRK CARGO LMTV W/EQP	253	96	112	23,621	10.71	10.71
07206G000	M1078A	1	TRK CARGO LMTV W/EQP	253	96	112	24,870	11.28	11.28
07206G000	M998A1	19	TRK UTIL CRG/TRP CARR	180	86	72	6,254	2.84	53.90
07206G000	M1113	1	TRK UTIL EXPANDED CAP	191	86	72	7,254	3.29	3.29
07206G000	M1083A	1	TRK CGO MTV W/EQP	274	96	112	23,979	10.88	10.88
07206G000	M1101	1	TLR CGO HIMOB 3/4-T	136	86	100	2,342	1.06	1.06
07206G000	M1101	1	TLR CGO HIMOB 3/4-T	136	86	100	2,274	1.03	1.03
07206G000	M1082	3	TRLR CGO LMTV FLATBED	210	96	102	11,230	5.09	15.28
07206G000	CAMEL	1	TRL TANK WTR 900 GAL	176	102	88	4,700	2.13	2.13
07206G000	20-FOO	1	20-FOOT CARGO CONTAIN	240	96	102	11,410	5.18	5.18

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07207G000	M113A3	1	CARRIER PERS FTRAC	210	100	100	23,880	10.83	10.83
07207G000	M2A3	14	FIGHTING VEH F/TRACK	258	129	142	64,858	29.42	411.87
07207G000	M1078A	1	TRK CARGO LMTV W/EQP	253	96	112	25,060	11.37	11.37
07207G000	M998A1	1	TRK UTIL CRG/TRP CARR	180	86	72	6,140	2.79	2.79
07207G000	M998A1	1	TRK UTIL CRG/TRP CARR	180	86	72	6,178	2.80	2.80
07207G000	M1083A	1	TRK CGO MTV W/EQP	274	96	112	24,937	11.31	11.31
07207G000	M1082	1	TRLR CGO LMTV FLATBED	210	96	102	10,660	4.84	4.84
07207G000	CAMEL	1	TRL TANK WTR 900 GAL	176	102	88	4,700	2.13	2.13
07207G000	20-FOO	1	20-FOOT CARGO CONTAIN	240	96	102	9,798	4.44	4.44
07207G000	20-FOO	1	20-FOOT CARGO CONTAIN	240	96	102	10,600	4.81	4.81
	PLS – M1075/M10 76	6	TR: 60'0" wall to wall Height w/8'6" TEU	62'2"	8'6"	10'8"/1 4'9"	76,382	34.65	207.88
	M109A6 Howitzer	8		35'3"	10'8"	11'11"	56,400	25.58	204.66
	M1088/M12 9A4	1		54'10"	8'0"	12'6"	37,060	16.81	16.81
	M1A2	29	Combat loaded wt: 138,800 lbs	29'7"	12'0"	10'2"	128,679	58.37	1692.68
	M2A3	38		21'6"	10'9"	11'10"	64,858	29.42	1117.94
	M88A1	3	Tank retriever	26'11"	12'0"	11'2"	107,840	48.92	146.75
	M88A2	6	Tank retriever	28'5"	12'0"	10'3"	139,450	63.25	379.52
	M978A	12	55,665 lbs with fuel	33'5"	8'0"	9'4"	38,230	17.34	208.09

Appendix 3: Rigging Rope Data

Lifting & Safety Services (www.lifting-safety.co.uk)

Size Nom.	6 x 19		Size Nom.	6 x 36						
Dia	Fibre Core	Steel Wire Core		Dia	Fibre Core	Steel Wire Core				
(mm)	Minimum Breaking	Approx Weight	Minimum Breaking	Approx Weight		(mm)	Minimum Breaking	Approx Weight	Minimum Breaking	Approx Weight
	Load (tonnes)	(Kg/100m)	Load (tonnes)	(Kg/100m)			Load (tonnes)	(Kg/100m)	Load (tonnes)	(Kg/100m)
8	3.81	23.2	4.11	25.5		8	3.8	23.6	4.1	26
9	4.83	29.3	5.22	32.2		9	3.8	23.6	4.1	26
10	5.96	36.2	6.44	39.8		10	5.94	36.9	6.42	40.6
11	7.21	43.8	7.79	48.2		11	7.19	44.7	7.77	49.2
12	8.58	52.1	9.27	57.3		12	8.55	53.2	9.23	58.5
13	10.1	61.1	10.9	67.2		13	10	62.4	10.8	67.2
14	11.7	70.9	12.6	78		14	11.6	72.3	12.5	79.5
16	15.3	92.6	16.5	102		16	15.2	94.5	16.4	104
18	19.3	117	20.8	129		18	19.2	120	20.7	132
19	21.5	131	23.2	144		19	21.4	133	23.1	146
20	23.8	145	25.7	160		20	23.8	148	25.7	163
22	28.8	175	31.1	193		22	28.7	179	31	197
24	34.3	208	37	229		24	34.2	213	36.9	234
26	-	-	43.5	270		26	40.1	250	43.3	275
-	-	-	-	-		28	46.6	289	50.3	318
-	-	-	-	-		32	-	-	65.7	416
-	-	-	-	-		35	-	-	78.5	497
-	-	-	-	-		36	-	-	83.2	526
-	-	-	-	-		38	-	-	92.6	586
-	-	-	-	-		40	-	-	103	650
-	-	-	-	-		44	-	-	124	787
-	-	-	-	-		48	-	-	148	935
-	-	-	-	-		52	-	-	174	1100

Appendix 4: ISO Tank Graph Input Data (Sample)

ISO Container			
Length (m)	Width (m)	Height (m)	Volume(m ³)
6.1	2.44	2.59	25.7867

		3 ISO Containers		4 ISO Containers		6 ISO Containers		8 ISO Containers	
Temp (deg C)	Temperature (K)	Pressure (Pa)	Bar	Pressure (Pa)	Bar	Pressure (Pa)	Bar	Pressure (Pa)	Bar
15.00	288.00	89786253	897.86	67339690	673.40	44893127	448.93	33669845	336.70
14.00	287.00	89474496	894.74	67105872	671.06	44737248	447.37	33552936	335.53
13.00	286.00	89162738	891.63	66872053	668.72	44581369	445.81	33436027	334.36
12.00	285.00	88850980	888.51	66638235	666.38	44425490	444.25	33319117	333.19
11.00	284.00	88539222	885.39	66404417	664.04	44269611	442.70	33202208	332.02
10.00	283.00	88227464	882.27	66170598	661.71	44113732	441.14	33085299	330.85
9.00	282.00	87915706	879.16	65936780	659.37	43957853	439.58	32968390	329.68
8.00	281.00	87603949	876.04	65702961	657.03	43801974	438.02	32851481	328.51
7.00	280.00	87292191	872.92	65469143	654.69	43646095	436.46	32734572	327.35
6.00	279.00	86980433	869.80	65235325	652.35	43490216	434.90	32617662	326.18
5.00	278.00	86668675	866.69	65001506	650.02	43334338	433.34	32500753	325.01
4.00	277.00	86356917	863.57	64767688	647.68	43178459	431.78	32383844	323.84
3.00	276.00	86045159	860.45	64533870	645.34	43022580	430.23	32266935	322.67
2.00	275.00	85733402	857.33	64300051	643.00	42866701	428.67	32150026	321.50
1.00	274.00	85421644	854.22	64066233	640.66	42710822	427.11	32033116	320.33
0.00	273.00	85109886	851.10	63832415	638.32	42554943	425.55	31916207	319.16
-1.00	272.00	84798128	847.98	63598596	635.99	42399064	423.99	31799298	317.99
-2.00	271.00	84486370	844.86	63364778	633.65	42243185	422.43	31682389	316.82
-3.00	270.00	84174613	841.75	63130959	631.31	42087306	420.87	31565480	315.65
-4.00	269.00	83862855	838.63	62897141	628.97	41931427	419.31	31448571	314.49
-5.00	268.00	83551097	835.51	62663323	626.63	41775548	417.76	31331661	313.32
-6.00	267.00	83239339	832.39	62429504	624.30	41619670	416.20	31214752	312.15
-7.00	266.00	82927581	829.28	62195686	621.96	41463791	414.64	31097843	310.98
-8.00	265.00	82615823	826.16	61961868	619.62	41307912	413.08	30980934	309.81
-9.00	264.00	82304066	823.04	61728049	617.28	41152033	411.52	30864025	308.64
-10.00	263.00	81992308	819.92	61494231	614.94	40996154	409.96	30747115	307.47
-11.00	262.00	81680550	816.81	61260412	612.60	40840275	408.40	30630206	306.30
-12.00	261.00	81368792	813.69	61026594	610.27	40684396	406.84	30513297	305.13
-13.00	260.00	81057034	810.57	60792776	607.93	40528517	405.29	30396388	303.96
-14.00	259.00	80745276	807.45	60558957	605.59	40372638	403.73	30279479	302.79
-15.00	258.00	80433519	804.34	60325139	603.25	40216759	402.17	30162569	301.63

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-16.00	257.00	80121761	801.22	60091321	600.91	40060880	400.61	30045660	300.46
-17.00	256.00	79810003	798.10	59857502	598.58	39905001	399.05	29928751	299.29
-18.00	255.00	79498245	794.98	59623684	596.24	39749123	397.49	29811842	298.12
-19.00	254.00	79186487	791.86	59389866	593.90	39593244	395.93	29694933	296.95
-20.00	253.00	78874730	788.75	59156047	591.56	39437365	394.37	29578024	295.78
-21.00	252.00	78562972	785.63	58922229	589.22	39281486	392.81	29461114	294.61
-22.00	251.00	78251214	782.51	58688410	586.88	39125607	391.26	29344205	293.44
-23.00	250.00	77939456	779.39	58454592	584.55	38969728	389.70	29227296	292.27
-24.00	249.00	77627698	776.28	58220774	582.21	38813849	388.14	29110387	291.10
-25.00	248.00	77315940	773.16	57986955	579.87	38657970	386.58	28993478	289.93
-26.00	247.00	77004183	770.04	57753137	577.53	38502091	385.02	28876568	288.77
-27.00	246.00	76692425	766.92	57519319	575.19	38346212	383.46	28759659	287.60
-28.00	245.00	76380667	763.81	57285500	572.86	38190333	381.90	28642750	286.43
-29.00	244.00	76068909	760.69	57051682	570.52	38034455	380.34	28525841	285.26
-30.00	243.00	75757151	757.57	56817863	568.18	37878576	378.79	28408932	284.09
-31.00	242.00	75445393	754.45	56584045	565.84	37722697	377.23	28292023	282.92
-32.00	241.00	75133636	751.34	56350227	563.50	37566818	375.67	28175113	281.75
-33.00	240.00	74821878	748.22	56116408	561.16	37410939	374.11	28058204	280.58
-34.00	239.00	74510120	745.10	55882590	558.83	37255060	372.55	27941295	279.41
-35.00	238.00	74198362	741.98	55648772	556.49	37099181	370.99	27824386	278.24
-36.00	237.00	73886604	738.87	55414953	554.15	36943302	369.43	27707477	277.07
-37.00	236.00	73574847	735.75	55181135	551.81	36787423	367.87	27590567	275.91
-38.00	235.00	73263089	732.63	54947317	549.47	36631544	366.32	27473658	274.74
-39.00	234.00	72951331	729.51	54713498	547.13	36475665	364.76	27356749	273.57
-40.00	233.00	72639573	726.40	54479680	544.80	36319787	363.20	27239840	272.40
-41.00	232.00	72327815	723.28	54245861	542.46	36163908	361.64	27122931	271.23
-42.00	231.00	72016057	720.16	54012043	540.12	36008029	360.08	27006022	270.06
-43.00	230.00	71704300	717.04	53778225	537.78	35852150	358.52	26889112	268.89
-44.00	229.00	71392542	713.93	53544406	535.44	35696271	356.96	26772203	267.72
-45.00	228.00	71080784	710.81	53310588	533.11	35540392	355.40	26655294	266.55
-46.00	227.00	70769026	707.69	53076770	530.77	35384513	353.85	26538385	265.38
-47.00	226.00	70457268	704.57	52842951	528.43	35228634	352.29	26421476	264.21
-48.00	225.00	70145510	701.46	52609133	526.09	35072755	350.73	26304566	263.05
-49.00	224.00	69833753	698.34	52375314	523.75	34916876	349.17	26187657	261.88
-50.00	223.00	69521995	695.22	52141496	521.41	34760997	347.61	26070748	260.71
-51.00	222.00	69210237	692.10	51907678	519.08	34605118	346.05	25953839	259.54
-52.00	221.00	68898479	688.98	51673859	516.74	34449240	344.49	25836930	258.37
-53.00	220.00	68586721	685.87	51440041	514.40	34293361	342.93	25720020	257.20

Appendix 5: 'Hydrogen Storage' Information

[MatWeb](#), The Online Materials Database

AISI Type 302 Stainless Steel, cold rolled to 1550 MPa tensile strength

Subcategory: Ferrous Metal; Heat Resisting; Metal; Stainless Steel; T 300 Series
Stainless Steel

Close Analogs: AISI Type 302B

Component	Wt. %
C	Max 0.15
Cr	18
Fe	70
Mn	Max 2
Ni	9
P	Max 0.045
S	Max 0.03
Si	Max 1

Material Notes:

Austenitic Cr-Ni stainless steel. More corrosion resistant than Type 301 and because of higher Ni content does not work harden as quickly as Type 301. Essentially non-magnetic in annealed condition, slightly magnetic in cold worked condition. Can be stamped, blanked, formed, and lightly drawn. Applications include car and radar antennas, automobile trim, bottling machinery, dairy processing equipment, food processing equipment, home appliances, hospital equipment, industrial floor plate, jewelry, kitchen and restaurant equipment, spring clips, washers, retainers.

Physical Properties	Metric	English	Comments
Density	7.86 g/cc	0.284 lb/in ³	
Mechanical Properties			
Tensile Strength, Ultimate	1550 MPa	225000 psi	
Modulus of Elasticity	193 GPa	28000 ksi	
Poisson's Ratio	0.25	0.25	Calculated
Izod Impact	23 J	17 ft-lb	
Fatigue Strength	485 - 550 MPa	70300 - 79800 psi	T302 with full hardened temper
Shear Modulus	77.2 GPa	11200 ksi	
Electrical Properties			
Electrical Resistivity	7.2e-005 ohm-cm	7.2e-005 ohm-cm	at 20°C, 0.000078 Ohm-cm at 100°C, 0.000086 Ohm-cm at 200°C, 0.0001 Ohm-cm at 400°C
Thermal Properties			

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CTE, linear 20°C	17.2 $\mu\text{m/m-}^\circ\text{C}$	9.56 $\mu\text{in/in-}^\circ\text{F}$	from 0-100°C
CTE, linear 250°C	17.8 $\mu\text{m/m-}^\circ\text{C}$	9.89 $\mu\text{in/in-}^\circ\text{F}$	at 0-315°C (32-600°F)
CTE, linear 500°C	18.4 $\mu\text{m/m-}^\circ\text{C}$	10.2 $\mu\text{in/in-}^\circ\text{F}$	at 0-540°C, 18.7 $\mu\text{m/m-C}$ at 0-650°C
Specific Heat Capacity	0.5 J/g-°C	0.12 BTU/lb-°F	from 0-100°C (32-212°F)
Thermal Conductivity	16.2 W/m-K	112 BTU-in/hr-ft²-°F	at 100°C (212°F), 21.5 W/m-K at 500°C (930°F)
Melting Point	1400 - 1420 °C	2550 - 2590 °F	
Solidus	1400 °C	2550 °F	
Liquidus	1420 °C	2590 °F	
Maximum Service Temperature, Air	870 °C	1600 °F	Intermittent Service
Maximum Service Temperature, Air	925 °C	1700 °F	Continuous Service

References are available for this material.

Spreadsheet Snapshot:

Pressure (Pa)	Pressure (bar)
4.60E+07	460

Cylinder Within an ISO Container (Spherical Ends)			
Inner Radius (m)	Length (m)	t (m)	Volume (approx) (m³)
1.09	6.1	0.13	22.76841
Weight (kg)			
45233.2285			

Material			
Stainless Steel Cold Rolled (AISI Type 302 Stainless Steel, cold rolled to 1550 Mpa tensile Strength)			
Density (kg/m³)	Ultimate Tensile Strength (Pa)	Fatigue Strength (Pa)	Poisson's Ratio
7860	1.55E+09	1.65E+09	0.25
Cylinder Wall Stress			
Hoop Stress	Pass		
385692307.7	Yes		
Cylinder End Stress			
Axial Stress	Pass		
192846153.8	Yes		

[MatWeb](#), The Online Materials Database

TIMETAL® 3-2.5 Titanium Alloy (Ti-3Al-2.5V; ASTM Grade 9) CWSR

Subcategory: Alpha/Near Alpha Titanium Alloy; Metal; Nonferrous Metal; Titanium Alloy

Key Words: Titanium 3-2.5; UNS R56320

Component	Wt. %
Al	2.5 - 3.5
C	Max 0.08
Fe	Max 0.25
H	Max 0.015
N	Max 0.03
O	Max 0.15
Ti	92.6 - 95.5
V	2 - 3

Material Notes:

Titanium content above is calculated as the remainder and may not reflect the actual range.

Cold Workable Medium Strength Alloy. UTS, TYS, and elongation data below are specific to CWSR condition; other specific condition entries are also available in MatWeb.

Features: Cold formable and weldable, this alloy is used primarily for honeycomb foil and hydraulic tubing applications. Industrial applications such as pressure vessels and piping also utilize this alloy. Available with palladium stabilization to enhance corrosion resistance. The alloy is cold formable and easily welded, such like the commercially pure grades of titanium. Yet the alloys offer nearly double the strength over TIMETAL 50A. It is ASME Boiler and Pressure Vessel code approved. It offers the highest structural efficiency of any of the common engineering metals approved by ASME. The alloy is available in all common product forms including billet, bar, plate, sheet, strip, tubing and pipe. It is nonmagnetic.

Typical heat treatment for this alloy: Stress Relief: 316-649°C for .5-3 hrs, air cool. Anneal: 649-760°C for 1-3 hrs, air cool. Solution treat: 871-927°C for .25-1 hrs, water quench. Aging: 482-538°C for 2-8 hrs, air cool.

Data provided by TIMET.

Physical Properties	Metric	English	Comments
Density	4.51 g/cc	0.163 lb/in ³	Typical
Mechanical Properties			
Tensile Strength, Ultimate	Min 862 MPa	Min 125000 psi	
Tensile Strength, Yield	Min 724 MPa	Min 105000 psi	
Elongation at Break	Min 10 %	Min 10 %	
Modulus of Elasticity	105 - 120 GPa	15200 - 17400 ksi	Typical
Poisson's Ratio	0.3	0.3	
Shear Modulus	43 - 45 GPa	6240 - 6530 ksi	
Electrical Properties			
Electrical Resistivity	0.000127 ohm-cm	0.000127 ohm-cm	
Thermal Properties			
CTE, linear 20°C	9.61 µm/m-°C	5.34 µin/in-°F	20-95°C
Thermal Conductivity	8.3 W/m-K	57.6 BTU-in/hr-ft ² -°F	20-95°C
Melting Point	Max 1700 °C	Max 3090 °F	
Liquidus	1700 °C	3090 °F	
Beta Transus	935 °C	1720 °F	

Spreadsheet Snapshot:

Pressure (Pa)	Pressure (bar)	Safety Factor (Ref: www.tateandale.com/asme_specs/index.html)
4.60E+07	460	4

Cylinder Within an ISO Container (Spherical Ends)				
Inner Radius (m)	Length (m)	t (m)	Volume (approx) (m ³)	
0.97	6.1	0.25	18.03114	

Weight (kg)
25954.4352

Material			
Titanium Alloy (TIMETAL 3-2.5 Titanium Alloy (Ti-3Al-2.5V; ASTM Grade 9) CWSR)			
Density (kg/m ³)	Ultimate Tensile Strength (Pa)	Yield Tensile Strength (Pa)	Poisson's Ratio
4510	8.62E+08	7.24E+08	0.3
Cylinder Wall Stress			
Hoop Stress	Pass		
178480000	Yes		
Cylinder End Stress			
Axial Stress	Pass		
89240000	Yes		

[MatWeb](#), The Online Materials Database

SGL Carbon Group SIGRAFIL C® C30 T045 EPY Continuous Tow Carbon Fiber with 45k filaments, Epoxy Sizing

Subcategory: Carbon; Carbon Fiber; Composite Fibers

Material Notes:

SIGRAFIL C as continuous tow is ideal for waving, prepregging, filament winding, Carbon Fiber Reinforced Plastics (CFRP) components, advanced composites, multi-axial production, unidirectional tapes, extrusion, pultrusion and other conversion processing. Characteristic properties of SIGRAFIL C include high tensile strength, high modulus of elasticity coupled with high electrical conductivity and compatibility with a large variety of resins.

Information provided by SGL Carbon Group

Physical Properties	Metric	English	Comments
Density	1.8 g/cc	0.065 lb/in ³	Fiber Density
Filament Diameter	7 µm	7 µm	
Mechanical Properties			
Tensile Strength at Break	3800 MPa	551000 psi	ASTM D3379-76
Elongation at Break	1.6 %	1.6 %	ASTM D3379-75
Modulus of Elasticity	225 GPa	32600 ksi	ASTM D3379-76
Electrical Properties			
Volume Resistivity	0.0015 ohm-cm	0.0015 ohm-cm	
Descriptive Properties			

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Aerostats for The Recovery of Disabled Main Battle Tanks and Other Heavy Military Equipment

Carbon Content, wt %	>95
Sizing Content, % by weight	0.5 - 1.8
Weight per unit length, g/m	3.3

Email Conversation with Roger Crane:

From: Crane, Roger M CIV NSWCCD W. Bethesda, 6550
Sent: Friday, June 22, 2007 13:59
To: Pink, Thomas D FORNATL-UK CIV NSWCCD West Bethesda, 2202
Cc: Dicks, Christopher A FORNATL-UK CIV NSWCCD W. Bethesda 2000
Subject: RE: Composite Fiber Pressure Vessels

Thomas,
I am not sure how large a vessel has been manufactured for high pressure gas storage using composite construction. I do not really see any major manufacturing issues with the exception of an inner liner. I would think that a polymer inner liner would be possible to keep weight down. Permeability is always an issue. I have a call into one of the manufacturers that I work with to see if they see any issues. I'll let you know what I find out.

Roger

-----Original Message-----

From: Pink, Thomas D FORNATL-UK CIV NSWCCD West Bethesda, 2202
Sent: Monday, June 11, 2007 13:36
To: Crane, Roger M CIV NSWCCD W. Bethesda, 6550
Cc: Dicks, Christopher A FORNATL-UK CIV NSWCCD W. Bethesda 2000
Subject: Composite Fiber Pressure Vessels

Roger Crane,

I'm currently working in code 2202 in the Center for Innovation in Ship Design (CISD) you were contacted last month concerning an intern's request for information, thank you for your help in answering his question. I wondered if I could also ask a question of my own, that you might (or someone you know of) be able to help me with.

I am currently working on a concept design project and I'm investigating storing large amounts of hydrogen gas. One method of storage is the use of composite fiber pressure vessels, which have the benefit of high strength combined with low weight.

I wondered how much you know about composite pressure vessels, I know they have been trialed successfully when storing small amounts of gas for use in hydrogen cars etc but has the technology been applied to larger storage capacities.

I'm looking to store roughly around 25m^3 at 400 bar, do you know of a composite fiber pressure vessel of this size ever being built? In your opinion how hard would it be to scale up the small pressure vessel to this storage capacity.

Any feedback you can give to this query would be greatly appreciated as so far I have found little information on the subject.

Thanks

Thomas Pink
UK MoD Graduate Engineer
Centre For Innovation in Ship Design
NSWC Carderock
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301-227-1480

Appendix 6: Electrolysis Unit Fact-sheet
(Source: Hydrogenics Corporation, HyStat-A Hydrogen Plants, Promotional Handout)

NB: All intellectual property rights remain with the company of origin.

on-site and on-demand

Benefits of IMET® Technology

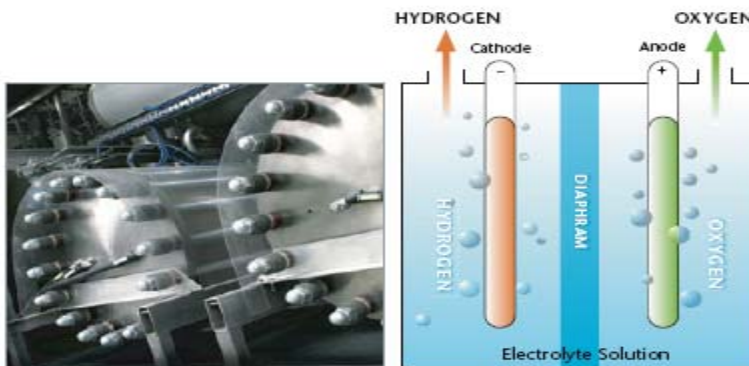
Quality from design to delivery	Stringent quality control procedures & factory tested to exacting standards.
Virtually maintenance-free	Pumpless electrolyte circulation; minimal moving parts.
On-site and on-demand production	Variable hydrogen production from 25 - 100% of capacity, ensuring quick automatic response to process demand.*
Reliable supply, and efficient delivery of hydrogen	> 98% availability; efficiently manage hydrogen inventories.
Flexibility to meet a customer's specific needs	IMET® is scalable producing from 1 Nm³/h to 60 Nm³/h (optional up to 120 Nm³/h) of hydrogen.
Multi-use system	IMET® generates argon and oil-free oxygen. Additional purification packages can be provided.
Easy to install	Delivered in plug & play packaging for indoor or outdoor use; minimal commissioning time; uses readily available water and electricity.
Safe operation	Asbestos-free; meets international codes and standards (PED, TÜV, ASME, CE, GOST, UL, AUS/NLZ).
Easy to use	Remote monitoring available; fully automated operation.

* Optional positive venting mode required under 25% capacity.

Hydrogen and oxygen are safely separated by the gas impermeable membrane. Hydrogenics is the only electrolysis manufacturer to develop and manufacture its membrane technology in-house, allowing for maximum quality control. Once separated, each gas flows via independent channels to gas separators where the gas is rinsed and cooled for the required process. Additional purification and drying systems are then applied as required to produce the desired level of purity.

IMET® Technology leads the industry with advanced safety and efficiency systems. Safety systems include continuous performance monitoring, preventive maintenance planning and 100% redundancy of critical components. In addition this Technology is highly efficient with an electrical consumption of 4.2 kWh per Nm³ of hydrogen produced (at cell stack steady state), and an overall system consumption of 4.8 kWh per Nm³ of hydrogen produced (including auxiliaries).

The HySTAT™-A Hydrogen Plant is a configurable system with standard options. The following pages will take you through seven key facts to consider when purchasing your HySTAT™-A Hydrogen Plant.



The standard HySTAT™-A hydrogen generator module is configured with our leading edge proprietary IMET® Technology.

Hydrogen Generation

HySTAT™ PRODUCTION						
Hydrogen Output	Nm³/h (scfh)	1-3 (38-114)	4-15 (152-570)	16-30 (608-1140)	31-45 (1178-1710)	46-60* (1748-2280)
Cell Stack Technology		IMET® 300 Series	IMET®1000 Series			
Number of Cell Stacks	—	1	1	2	3	4
Maximum Pressure	bar (psi)	25 (363)	10 or 25* (145 or 363)			
Cell Surface Area	cm² (in²)	300 (46.5)	1000 (155)			
Standard Purity	%	99.9**	99.9***			
Power Consumption (Electrolysis)	kWh/Nm³ (kWh/100scf)	4.2 (11.0)	4.2 (11.0)			
Power Consumption (inc. rectifier and auxiliaries)	kWh/Nm³ (kWh/100scf)	4.9 (12.9)	4.8 (12.6)			
Power Supply	—	380 - 600 VAC / 50 - 60 Hz, 3 phase				
Packaging	—	Indoor or outdoor operation - Alucobond enclosure Optional steel containers or ISO container (10', 20', 40')				
HySTAT™ PRODUCTION						
Oxygen Output	Nm³/h (scfh)	0.5-1.5 (19-57)	2.0-7.5 (76-285)	8-15 (304-570)	15.5-22.5 (589-855)	23-30* (874-1140)
Standard Purity	%	99.5**	99.5**			

Data is normalised to 0°C (32°F) and is for marketing purposes only.

* Larger systems available upon request.

** 25 bar max. pressure option - possible only up to 30 Nm³/h
and power consumption is 4.9 kWh/Nm³h

*** Up to 99.9995% purity can be achieved with purification packages

1. Generation Module Capacity

Hydrogenics offers on-site HySTAT™-A hydrogen generators rated at 1 Nm³/h (38 scfh) to greater than 60 Nm³/h (2280 scfh) of hydrogen production. The chart above outlines the specifications of each platform.

Oxygen production is readily available with additional equipment.

2. Feed Water Supply

The IMET® cell stack in the HySTAT™-A Generator module uses demineralized water. A Hydrogenics specialist will analyze your feed water supply data and, if needed, develop a water purifying package to be integrated into the HySTAT™-A Power Plant, ensuring the water meets the proper specification.

3. Cooling Water

Cooling water is required to cool the cell stacks as well as the gases. Potable water delivered at a minimum of 1 bar (14.5 psi) to a maximum of 7 bar (101 psi) is required. A Hydrogenics specialist will evaluate your cooling water supply and determine its suitability. As an option, a closed loop cooling water system can be provided to achieve the cooling water specifications.

Appendix 7: Future Steam Reforming

DISTILLATE FUEL PROCESSING FOR MARINE FUEL CELL APPLICATIONS

G. Steinfeld, R. Sanderson, H. Ghezel-Ayagh, S. Abens

FuelCell Energy, Inc.
3 Great Pasture Road
Danbury, CT 06811

Mark C. Cervi
Naval Surface Warfare Center
Carderock Division
Philadelphia, PA 19112

Prepared for Presentation at the AIChE Spring 2000 Meeting

March 5-9, 2000

Session TD004

Fuel Selection for Fuel Cell Based Power Systems

January, 2000

Unpublished

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March 5-9, 2000
Submitted January 17, 2000

Abstract

FuelCell Energy, Inc. (FCE) is developing a 625 kW fuel cell power plant for marine applications based on its Direct Carbonate Fuel Cell (DFC™) technology. The power plant is designed for operation on Mil-F-16884J Naval distillate fuel designated as NATO F-76. This fuel is characterized as a 385°C (max) end boiling point diesel fuel with up to 1% sulfur by weight. The development is part of the U.S. Navy 2500 kW Ship Service Fuel Cell Program, sponsored by the Office of Naval Research and administered by the Naval Surface Warfare Center Carderock Division.

The technical approach is based on adapting FCE's commercial Direct Fuel Cell technology for marine applications. This fuel cell system utilizes a mixture of alkali metal carbonates as the electrolyte and operates at 1100-1250°F where internal reformation of hydrocarbon fuels is feasible. Because the process waste heat is captured by the endothermic fuel reforming reaction, the DFC™ stack provides unsurpassed overall power plant efficiency.

Processing of this distillate fuel in the marine power plant design includes a high-pressure hydrodesulfurizing first stage producing desulfurized liquid fuel. The second stage employs an adiabatic prereformer, which reacts the desulfurized distillate with steam producing a methane rich fuel gas. The converted fuel is expanded through a turbo generator, reheated and directed to the anodes in the DFC™ stacks. The methane is then converted to hydrogen in the DFC™ stacks which in turn is electrochemically converted to water, thereby producing DC power. Water for steam is recovered from fuel cell exhaust making the process self-sufficient in its water needs.

Tests on sample batches of NATO F-76 supplied by the U.S. Navy have confirmed the processes of desulfurizing and adiabatic prereforming. Subscale tests of the hydrodesulfurizing process have reduced sulfur levels in the fuel to less than 100 ppb. Tests on the adiabatic prereforming stage have confirmed stable composition of the converted fuel. A 10-cell stack of FuelCell Energy's commercial nine square foot active-area has operated for over 1,000 hours to date producing power from the converted NATO F-76 distillate fuel, validating the fuel processor design.

Introduction

In 1997 the Office of Naval Research (ONR) initiated a three-phase advanced development program to demonstrate that commercially developed fuel cell technology can meet ship service power requirements for surface combatants. The initial phase of the ship service fuel cell (SSFC) program was focused on conceptual design and critical component testing. Phase 2 of the program includes detailed design, construction, and land-based testing of a 0.5 MW demonstration power plant by FuelCell Energy at its facility in Danbury, CT. The demonstration power plant will be delivered to the Naval Surface Warfare Center's Test Center in Philadelphia, PA in 2003 for additional land-based performance testing. Phase 3 of the program includes testing of the power plant at sea.

DFC technology is unique in that it can operate directly on hydrocarbon fuels without the use of an external reformer. The approach to processing of the NATO F-76 marine distillate fuel is based on desulfurization followed by adiabatic prereforming to a methane-rich gas which can be reformed internally by the fuel cell. This approach minimizes changes to the fuel cell power plant being developed by FCE for commercial applications.



FuelCell Energy
World Leader in Ultra-Clean Power

Demonstration of a Fuel Cell Power Plant for Co-production of Electricity and Hydrogen

FCE Project Manager: Pinakin Patel (ppatel@fce.com)

Project Sponsors: DOE-EERE and Air Products and Chemicals, Inc.

Period of Performance: 2005-2009

Introduction

One of the immediate challenges in the development of hydrogen as a transportation fuel is finding the optimal means to roll out a hydrogen-fueling infrastructure concurrent with the deployment of hydrogen vehicles. To meet this challenge, distributed generation of hydrogen has been proposed as a potential sourcing solution. However, the low-volume hydrogen requirements in the early years of fuel cell vehicle deployment and the sporadic nature of vehicle fueling make the economic viability of stand-alone, distributed hydrogen generators particularly challenging. One significant challenge for fueling station developers will be minimizing the financial risk associated with stranded capital assets. A potential solution to this “stranded asset” problem is the use of hydrogen energy stations that produce electricity in addition to hydrogen. One such station concept that shows promise, as concluded by APCI and DOE, is the use of high-temperature fuel cells to co-produce hydrogen and electricity. This concept has the potential to meet the DOE hydrogen cost targets, while producing power for less than \$0.10/kW. To validate this conclusion, a DFC-300 modified to allow for the separation and purification of hydrogen from the fuel cell anode exhaust using an Air Products-designed hydrogen purification system will be demonstrated. In addition to natural gas as a fuel, renewable digester gas fuel will be used for this demonstration for hydrogen co-production.

Objectives

Demonstrate the technical and economic viability of a hydrogen energy station using a high-temperature fuel cell designed to produce power and hydrogen from natural gas.

- Complete a technical assessment and economic analysis on the use of high-temperature fuel cells (HTFCs), including solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs), for the co-production of power and hydrogen from natural gas (energy park).
- Determine the applicability of HTFC co-production for the existing merchant hydrogen market and for the emerging hydrogen economy.
- Demonstrate the concept at a suitable site with demand for both hydrogen and electricity using natural gas and digester gas as fuels.



FuelCell Energy

World Leader in Ultra-Clean Power

facts

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Strategic Mfg. Development

Bruce Ludemann

Senior Vice President
Sales & Marketing

Joseph G. Mahler

Senior Vice President
Treasurer, Corp. Strategy

SHIPS SERVICE FUEL CELL POWER PLANT DEVELOPMENT

FuelCell Energy (FCE) is currently developing marine diesel applications for its DFC® technology under contracts with the U.S. Navy. Fuel cell based marine power plants possess the potential of superior performance with optimized fuel efficiency and environmental impact. The Office of Naval Research (ONR) and the Naval Sea Systems Command (NAVSEA) are conducting an advanced technology development program to develop and demonstrate fuel cell electric power generators for surface ship applications. A principal goal of the Navy's Ship Service Fuel Cell (SSFC) program is to demonstrate that commercially developed fuel cell technology can utilize naval logistic fuels and operate in a marine environment.

Megawatt-class direct carbonate fuel cell (DFC®) power plants are currently being marketed by FCE for distributed power generation applications using natural gas and digester gas fuels. Because of the unique ability of DFC® stacks to internally reform the methane in the fuels, DFC® plants can provide thermal efficiency approaching 50 percent over a wide range of operating power. To meet the Navy's shipboard power requirements, FCE is adapting the commercial DFC® technology for use with naval logistic fuels.

In the first phase of the SSFC program, FCE developed a conceptual design for a modular 2.5 MW first generation marine rated DFC® power plant and conducted critical component testing. The key features of this design include ability to operate with naval distillate fuels containing up to 1% sulfur, and internal process water recovery for water independent operation.

In the ongoing second phase, a logistic fuel processing and balance of plant (BOP) module for a 0.5 MW first generation demonstrator plant was designed and constructed. Process and Control (PAC) testing of the module verified conversion of high sulfur content Navy logistic fuels to anode fuel gas with composition transparent to the internal reforming carbonate fuel cell stack. For Factory Testing conducted at FCE's Danbury, CT facility, the BOP module was connected to an FCE commercial design DFC® fuel cell stack, and the integrated power plant was operated on-load for over 250 hours. On-board sulfur removal from the high sulfur logistic fuel and internal process water recovery from stack exhaust were verified. The power plant was shipped to Philadelphia during the summer of 2007 for additional evaluation at the NAVSEA test facility.

FCE is also participating in an ONR-sponsored second generation naval fuel cell development program aimed at substantially reducing the size and weight of the current first generation ships service fuel cell power plant. Toward this goal, FCE will investigate the feasibility of scaling up its high temperature polymer electrolyte fuel cell technology to power levels required in ship service power generators, and address approaches for reducing size and weight of the logistic fuel processing system.